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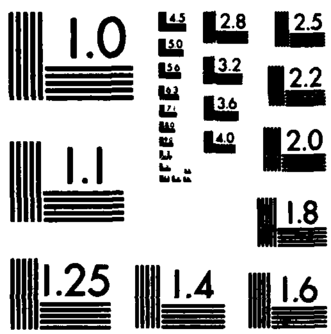

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ESTIMATING THE COST OF COMPOSITE MATERIAL AIRFRAMES USING THE RAND CORPORATION DEVELOPMENT AND PROCUREMENT COSTS OF AIRCRAFT PARAMETRIC MODEL (DAPCA III)

Gordon D. Kage, II, Major, USAF

LSSR 39-83

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER LSSR 39-83	2. GOVT ACCESSION NO. AD-A134 993	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ESTIMATING THE COST OF COMPOSITE MATERIAL AIRFRAMES USING THE RAND CORPORATION DEVELOPMENT AND PROCUREMENT COSTS OF AIRCRAFT PARAMETRIC MODEL (DAPCA III)		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Gordon D. Kage, II, Major, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Systems and Logistics Air Force Institute of Technology, WPAFB OH		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Communication AFIT/LSH, WPAFB OH 45433		12. REPORT DATE September 1983 13. NUMBER OF PAGES 139
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release: IAW AFR 190-17.

LYNN E. WOLAVER
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

15 SEP 1983

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Development and Procurement Costs of Aircraft (DAPCA III)
Parametric cost models
Composite material
Cost estimating
FACET
ICAM Manufacturing Cost/Design Guide

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Thesis Chairman: Richard L. Murphy

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The increasing use of composite material in airframes is effecting the accuracy of the current methods of estimating aircraft costs. Aluminum and composite material parts are fabricated and assembled using different processes which have different costs. Parametric models such as DAPCA III rely on a data base of all-aluminum aircraft to estimate the cost aircraft that have large amounts of composite material in them. Adjusting the estimates to reflect the composite material in the aircraft requires a detailed analysis of the composite part cost then substituting that cost for the comparable amount of aluminum. The three-step process is time consuming and inaccurate. This thesis has developed a series of indices which reflect the differences in manufacturing cost for composite parts and aluminum parts that can be applied directly to the DAPCA III output. They were developed by comparing identical parts made from aluminum and then from composites. The ICAM Manufacturing Cost/Design Guide estimated the aluminum part cost and the FACET computer program estimated the composite material part cost. Indices are provided for nonrecurring tooling manhours, recurring manufacturing manhours, and material dollar costs.

LSSR 39-83

ESTIMATING THE COST OF COMPOSITE MATERIAL AIRFRAMES USING THE RAND CORPORATION DEVELOPMENT AND PROCUREMENT COSTS OF AIRCRAFT PARAMETRIC MODEL (DAPCA III)

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Management

by

Gordon D. Kage, II, BS, MA
Major, USAF

September 1983

This thesis, written by

Major Gordon D. Kage, II

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS MANAGEMENT

DATE: 28 September 1983

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ACKNOWLEDGMENTS

This thesis effort would not have been possible without the support of numerous individuals. Mr. Stan Nisevich, Aeronautical Systems Division Cost Research Division Analyst, gave continuous support and a wealth of cost analysis information that made the thesis possible. Mr. Harry S. Reinert, Materials Laboratory Program Manager for numerous composite material research projects explained composite material production problems, processes and analysis of the current state-of-the art better than any other sources of information. Mr. Cecil D Wallace of the Flight Dynamics Laboratory Structures Preliminary Design Group was the "Rosetta Stone" for this thesis, providing the necessary translation information that enabled comparable aluminum and composite material parts to be built. Mr. K. Evan Gray of Advanced Data Management Corporation, Princeton New Jersey, provided selfless computer support in the form of unlimited access to their corporate version of the FACET computer program. The thesis advisory team, Mr. Rich Murhpy, Chairman, with Major Ron Rasch and Lieutenant Commander Joe Stewart as readers were supportive and effective in helping to develop this thesis. Finally, my wife, Pamela, provided support, motivation, proof reading and consolation whenever it was needed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background

Each year, the Department of Defense (DOD) must justify military projects to the Congress to receive authorization and appropriations. Inadequate explanations of project costs can result in congressional distrust of DOD estimates or misallocation of those appropriations. As DOD projects increase in complexity, or introduce new technology such as composite material, their costs become more difficult to predict and subject to increased debate. The cost of projects such as the F-18, AV-8B, and B-1B which incorporate advanced composite material, have been debated in the national press as well as in government circles. Understanding the impact of composite materials on cost is important when examining the cost of such aircraft.

Composite materials differ from metal in several ways. They are constructed by layering fine fibers in a matrix of bonding medium, either an epoxy resin or a polyimide. Individually, the fibers have very little strength, but when layered together and bonded in a matrix, they have a tensile strength (ability to withstand being pulled apart) double that of metals used in aircraft (17:vol.1,p.2-2). Additionally, they are on the average about 15 to 20 percent lighter than a comparable metal part (7:A.6). Composites have different heat, corrosion, and impact qualities than

metal as well. As a result, the fabrication and assembly methods are different. To account for these differences, the early cost estimates for airframes using composites were determined by a three-step process.

The process required separate estimating methods for metal and composite components. Estimates for all-aluminum airframes were developed with a parametric cost model. Estimates for the composite material to replace some of the aluminum were developed using a work breakdown structure (WBS), a detailed description and coding of the steps in the manufacturing and fabrication processes, expressed in labor hours. The dollar value of the labor and the materials used were combined to provide the cost of each composite part. The difference between the cost of the modified sections when made of composite material instead of metal was then used to adjust the original metal airframe estimate. Necessarily, many assumptions about the manufacturing and assembly processes were needed to get a reliable estimate for the composite sections. Poor estimates of the composite parts made little difference in the end because the parts represented just a fraction of the total weight and cost. However, the increasing use of composites, 26 percent airframe weight for the AV-8B, is making the three-step method both inefficient and inaccurate. A method of successfully incorporating advanced composite material technology into parametric estimates is needed.

Problem

The Department of Defense needs an estimating model to determine the cost of a composite material aircraft airframe. The Air Force Flight Dynamics Laboratory has contracted for a model that will predict the cost of composites in complex airframes. The contract, F33615-81-C-5122, is in excess of $400,000. At the same time, Mr. Gibson (6), chief of the Aeronautical Systems Division (ASD) Cost Research Branch (ASD/ACCR) identified a need for a reliable method of modifying the existing metal based parametric estimating models to reflect the increasing use of composites. This thesis will examine both modifying a cost model to predict composite material costs and developing one.

Developing a model that can predict the cost of airframes with large quantities of composite material in them poses several problems. The first problem is to determine the approach to the model. The most common approach for estimating aluminum airframes has been regression analysis. Regression analysis provides a method of statistically comparing models as well as evaluating the probability of the final answer being correct. This research will examine the feasibility of a composite material airframe model developed using regression analysis methods.

One of the most significant problems in regression

analysis is defining the independent variables. These "cost drivers" are the characteristics of the item to be analyzed that affect its cost. There are three main approaches to the problem of cost drivers in developing a cost model for composite airframes: 1) a model with cost drivers based on physical and performance characteristics of the airframe such as speed, weight, or best altitude, 2) a model based on the physical and performance characteristics of the composite material used such as weight, volume, thickness, or heat sensitivity, and 3) a model based on the type of manufacturing method (automated, semi-automated or manual) used in producing the material broken down into individual WBS elements. Each of approach uses a different data base for cost estimating.

The airframe performance characteristics approach requires a data base of aircraft with large amounts of composites to be able to accurately estimate composite airframe costs. Some of the parametric cost models that have recently been introduced include aircraft like the F-14 and the F-16 which do incorporate some composite material into their airframes. Their impact on the regression equations is minimal because these aircraft have relatively little amounts of composite material, less than 15 percent, and represent only two data points in data sets of 20 or more.

The composite parts characteristics approach requires

enough historical data on previously constructed parts to estimate a composite airframe. The data on every part that has been developed is available, but a composite airframe will still be over 50 percent metal (7:D.8) so an estimate for the metal must be developed separately.

Manufacturing method models which rely on the work breakdown structure can be used with any combination of parts, but the manufacturing methods must be fixed before a reasonable estimate can be developed, thus they are not suitable for early planning.

A second problem in developing a cost model for directly estimating composite material airframes is massing the data necessary for reliable parametric estimation. Currently, there is only one aircraft with more than 20 percent composite material, the AV-8B which is not yet in production (7:D.8). Other aircraft such as the F-14, F-15, F-16, and F-18 incorporate some composite materials, but the amount is less than 15 percent of the airframe weight. There are less than 10 aircraft in the inventory with significant quantities of composite materials. Using regression analysis of a data set with just those aircraft in it to make cost predictions about composite airframes would not provide results that could be used with any degree of confidence.

Data validity is the third problem in developing a cost model. A valid data base is both an accurate representation

of what was measured and a reliable predictor of what is to be measured. Inaccurate cost information for previous aircraft will result in poor estimates of future aircraft. Likewise, accurate estimates of cast iron stoves are not likely to produce reliable estimates of composite airframes. The cost data that is used should be accurate and applicable to building composite airframes. The limited percentages of composite material in current aircraft are parts which have been introduced as direct substitutions for metal parts. As the percentages of composite material in airframes increase, different assembly and design methods may be used that would make the current data invalid. A possible method for using data not directly capable of predicting the cost of a composite airframe would be to determine what cost drivers are common to metal airframes and composite airframes and how the cost drivers are related to each other. For example, weight could affect cost in a metal as well as a composite material airframe. As more metal or composites are used, the costs should increase, though most likely not exactly the same way. If the relationship could be determined, the metal airframe estimate could be adjusted for the difference. Thus, a valid data base for metal aircraft could be used for composite airframes if adjustments for differences could be accounted for.

One of the most reliable metal airframe parametric models is the Rand Corporation Development and Procurement

Cost of Aircraft model (DAPCA III) (11:46). It is based on Aeronautical Manufacture's Planning Report (AMPR) weight (airframe unit weight) and maximum speed in knots at best altitude. AMPR weight is defined as follows (2:1):

> The empty weight of the airplane less (1) wheels, brakes, tires and tubes, (2) engines, (3) starter, (4) cooling fluid, (5) rubber or nylon fuel cells, (6) instruments, (7) batteries and electrical power supply and conversion equipment, (8) electronic equipment, (9) turret mechanism and power operated gun mounts, (10) remote fire mechanism and sighting and scanning equipment, (11) air-conditioning units and fluid, (12) auxiliary power plant unit, and (13) trapped fuel and oil.

DAPCA III uses the two performance parameters to determine the cost of a future airframe by examining a data base of performance characteristics for aircraft constructed earlier in time with known performance and cost values. The aircraft used in the DAPCA III are aluminum aircraft with only limited amounts of other metals and very few composite parts, if any. This Rand Corporation model could be used to predict the cost of composite material airframes if it could be adjusted to reflect the addition of composite material. Once the adjustment factors are known, the current three-step process can be eliminated.

Research Objective

The reseach objective of this thesis is to develop an index of adjustment factors that will reflect the differences between aluminum and composite material airframe costs. The index will be designed for use with the Rand

DAPCA III model. The index should eliminate two steps of the cost estimating process now being used. Before the Rand Corporation model can be successfully adjusted, several research questions must be answered.

Research Questions

The first research questions concern the Rand DAPCA III model. Is it the best possible airframe model available? How valid are the data used to construct it? How can modifications to the model be verified? Before the Rand model can be selected over the other airframe models, the cost model literature must be reviewed and the comparative advantages of the other models that are currently available evaluated. The comparison process will be to examine the Rand data base and cost estimating methodology then compare the findings to the data bases and cost estimating relationships used by other models. The process should determine if any other model has such significantly better characteristics and wider application that it warrants being selected over the DAPCA III model as the format for the index development.

The remainder of the research questions concern the process of developing the index and establishing its validity. First, how should the index be developed? Second, how should the data used to develop the index be collected, used, and validated? Finally, the resulting index must be examined for validity and tested for

sensitivity to changes in the data. Additionally, the possibility of generalizing the index for use in other models should be examined. Answering these questions will contribute directly to the thesis objective.

Methodology Summary

The index will be developed by comparing materials, labor and tooling cost of composite parts to metal parts. The size of the parts will range from simple panels and ribs to larger structures such as horizontal stabilizers, ailerons and fuselage sections. The parts will be a representative sample of the types of parts that will be used in aircraft airframes that consist of 10 to 40 percent composite material, whether they are bomber, fighter or transport. The larger parts will account for the design and assembly differences as the amount of composites in the airframe increase. The smaller parts will reflect the differences in fabrication methods.

The method of comparing costs will be to take a metal part or structure, design it out of composite material, and then compare the costs of the two items. Since historical airframe costs are not normally broken down to the part level, it will be necessary to use a model that will estimate the cost of such parts. Similarly, since the composite part is a contrived part, its cost must also be estimated. The validity of the resulting index rests on the accuracy of the models that are used to develop the cost of

the parts.

The accuracy of the models will be examined by comparing model estimates to actual cost information. Additional tests will be accomplished to test the sensitivity of the index to changes in model parameters.

Scope

The objective of the thesis is to develop an index that accurately reflects the differences between composites and metal. The DAPCA III model is being used to establish a format for the index and a basis for discussing the differences between metal and composite costs. No adjustments will be made to the DAPCA III cost estimating relationship (CER) equations, or data base. Therefore, the the index can be developed and validated to meet the research objective without actually using the DAPCA III computer program. Before the research objective can be reached, however, a thorough review of the literature must be completed. Additionally, greater explanation of the methodology is needed to clarify statistical approaches to the problem.

CHAPTER II

MATERIAL DIFFERENCES AND COST MODELS

Introduction

To fully understand the problems associated with developing a cost model incorporating composite material, it is necessary to examine the many different ways that composite material parts can be fabricated and assembled. Different composite material parts or designs may require unique treatment just as different types of metal alloys have different properties and manufacturing processes.

There are several different types of composite material fibers being used in the airframe manufacturing industry. The three most common are carbon based (graphite), boron, and Kevlar, a glass-like material. They can be laid into the matrix as single filaments (monofilament), woven fabric (broadcloth), or unidirectional tape. The most common bonding media are epoxy resins that have a maximum service temperature of about 350 degrees (temperature they can stand before loosing their strength and structural properties), but greater temperature resistant polyimids for use in engines and other high temperature areas are being developed (17:vol.1,p.2-5). Some epoxies have limited life spans, once opened, they must be used quickly or they will harden and become unusable. The manufacturing process used to combine the fabrics and the bonding mediums into composite material aircraft parts is a multi-step process with many

options for the processes.

Composite Material Manufacturing Process

The general process, as outlined in the DOD/NASA Structural Composites Fabrication Guide(17), consists of lay-up, the layering of the fibers; debulking, removal of air and moisture from between the layers; curing, baking the structure under pressure to set the epoxy resins; and cutting the structure to final specification.

Lay-up can be done manually, by machine, or by robot. Manual lay-up is time consuming and requires skilled workers, but has little initial investment cost. Manufacturing time decreases as machines and robots are used, but initial investment increases. According to Mr. Harry S. Reinert (16), Air Force project officer for the DOD/NASA Structural Composites Fabrication Guide, manual lay-up is most frequently used for prototyping instead of production. In the last five years, tape laying machines have become the most common method of production in the airframe industry.

Debulking costs depend on the lay-up method, number of plies, and type of material. For example, machine layed fibers are tighter and need not be debulked every layer. Still, in fabricating a complex, relatively thick part, as many as 10 to 15 debulks may be required (17:vol.1,p.6-25). To help alleviate the problem, the industry has developed new fiber/epoxy combinations which do not require debulking.

Curing costs depend on the initial investment in an autoclave, a high pressure oven, and the method of curing preparation. If a firm chooses not to invest in a large autoclave they must build smaller parts that will fit in a smaller autoclave. The smaller parts require additional assembly labor and have a higher amount of wasted material relative to larger parts. A large autoclave, while more expensive, can cure large sections such as wing panels or "cocure" complete subassemblies which reduces assembly labor cost. Cocuring is the process of curing several different parts simultaneously making them into a single structure by joining them together with material and epoxy. Preparation for curing requires "bagging" the material to provide a controlled atmosphere. There is a 32 percent savings in labor alone if the reusable bagging system is chosen (17:vol 1,fig.6.48). Work is progressing on composite material and mechanical tape laying machine combinations that allow both debulk and cure steps to be accomplished during lay-up. This method is still very new and will not be available for use in the near future.

Labor costs for cutting the composite parts also vary with the method used. Parts can be cut several ways: by a laborer with a sharp knife and a template; a Gerber reciprocating knife cutting device similar to a paper cutter in principle; a computer guided laser; or a computer guided high pressure stream of water. The greater the automation,

the fewer laborers required but the higher the intitial investment.

As a final consideration, each different manufacturing method requires a different adjustment to the standard hours to determine the cost. Standard hour rates are developed using industrial engineering practices such as motion-time-measurement (MTM) studies and historical averages of how long it took to do an assembly task. They are designed to reflect only the work content in a process and none of the production time variances caused by humans or machines such as coffee breaks, fatigue, and equipment failures. Standard hours can provide a basis for comparing processes. The actual cost of an item is determined by multiplying the standard hour time by a realization factor. Realization factors are defined by the ICAM _Manufacturing Cost/Design Guide_ as (12:p.2-10):

> Those factors which account for the percentage difference between standard hours and actual shop performance in the airframe industry. Realization factors represent elements, which are generally applied as multipliers to the base standard hours, to arrive at an "estimated real time" total cost to manufacture a part.

A company with automated equipment will most likely have higher overhead, but less labor variance than a company relying on manual lay-up. Thus different companies will have different standard hours and realization factors.

Understanding these many methods of manufacturing and cost considerations provides insight into the cost models

that have been developed for composite material. The two methods that have been developed expressly for composite material are the Advanced Composites Cost Estimating Manual (ACCEM) (AFFDL-TR-76-87), and its follow-on, Fabrication Cost Estimating Technique (FACET).

Composite Material Cost Models

ACCEM. The ACCEM is a computer based system that uses a complete work breakdown structure approach to develop the cost of a part. The cost is determined by summing the labor hours required to produce the parts and the labor hours required to assemble them. The Grumman Corporation used the system to compare the predicted ACCEM values to their actual cost values for producing F-14 horizontal stabilizers under Air Force Flight Dynamics Laboratory contract number AFFDL-TR-79-3041. The system required each step, lay-up, debulking, curing, and cutting be further divided into functional areas. The lay-up procedure alone required over 30 entries into the computer program. The resultant cost estimate was an average of 10 percent low for graphite epoxy parts and 40 percent low for fiberglass epoxy parts. The largest deviations were in estimating large or complex parts because ACCEM did not account for more than one worker performing a task, nor did it consider complicated, combined processes such as forming shapes with many angles. The Grumman Corporation concluded by recommending that the cost estimating relationships be modified to account for changing

production schedules, the number of tools used to produce a part and the type of material being worked. In addition to the modifications, they requested changes in the detail of the work breakdown structure to allow it to account for more than one worker. The closing remark was (15:54):

> The ACCEM program in its present configuration is too laborious to use in detail design, and not suited at all for preliminary design. Use in detail design with some program restructuring could eliminate a great deal of part modeling and keypunch/remote terminal entry time.

The reduced keypunch/remote terminal entry time refers to the Grumman labor accounting practices. The problems with ACCEM in developing an airframe model are many. Grumman clearly states that it is too cumbersome for early design work. Its total reliance on a work breakdown structure made it very "laborious" to use. The successor model, FACET, is an enhanced version of the ACCEM published in the DOD/NASA Structural Composites Fabrication Guide (17).

FACET. The FACET model grew out of a joint Air Force Materials Laboratory and civilian industry effort to develop a data base of composite material cost information that could be used for parametric estimation of composite material costs. The data base, published in the DOD/NASA Structural Composites Fabrication Guide (17:vol.2), is organized like the Rand Corporation airframe data base. It consists of descriptions of all of the parts that have been made, labor hours required for each step in the process, and material used in pounds. The material used in pounds is a

great help because composite material costs have gone from hundreds of dollars per pound in the mid 1970s to under 50 dollars per pound for most materials now. The labor hours required for each step were either the actual hours or adjusted hours derived through MTM studies. The FACET model data base uses the cost element structure shown in Table 1 (17:vol.1,fig.6-52):

COST OF ADVANCED COMPOSITE PART

NONRECURRING COSTS	RECURRING COSTS
Direct Material Dollars	Direct Material Dollars
engineering material tooling	production material tooling
Direct Labor Hours	Direct Labor Hours
engineering hours tooling hours manufacturing engineering quality control	engineering hours tooling hours manufacturing engineering quality control graphics direct factory

INDIRECT COSTS

engineering overhead
manufacturing overhead
material overhead
general and adminsitration

Figure 1

The data base consists of 244 composite material parts made by 24 different companies. The parts are used in fighter, bomber, transport, and helicopter aircraft (17:vol.2,pp.A17-A27). The three main elements of the data base are the cost element structure shown above, a

description of the physical part, and the method of construction of the part. The output is expressed in tooling, labor hours, and material useage for each step in the fabrication process. This information can also be expressed in a format for modifying the DAPCA III model. The FACET model has been the more accurate parametric method of predicting costs of individual composite materials and can provide an excellent vehicle to use in developing an index to use in modifying all-aluminum cost estimates. It is not a good composite airframe cost predictor on its own because it does not estimate the metal that would have to be used and requires a summation of the parts. The output of the model, material costs in pounds and labor hours makes it ideal to work with because dollar values are not used in developing the estimate. The methods that are used in fabricating and assembling composite parts differs significantly from the methods used in fabricating metal parts.

Aluminum Manufacturing Methods

The processes for fabricating and assembling aluminum parts are described in the ICAM Manufacturing Cost/Design Guide, volumes 1-3 (12). Unlike composite material where every part is shaped in lay-up and cutting, metal parts are shaped in a variety of ways. Sheet metal can be stamped, rolled, or bent depending on the desired final shape (12:vol.1,fig.4.1-3). Additionally, aluminum can be cast or

milled to form complicated or very thick parts.

Sheet metal working requires a brake and roll press to be rolled or a brake stretch press to be bent. They are large hydraulically assisted machines run by a skilled operator. Complex metal contours may require more than one operation if they are not stamped on a rubber press. A rubber press forces the aluminum into a mold to shape the part. A new rubber mold must be developed for each different part. Once the parts are formed, they must be reheated, annealed, to strengthen them if the contours are severe.

Aluminum parts that are formed by casting or milling require extensive machining. For example, a part that is an inch thick bulkhead with a three inch lip that is U-shaped to fit the contour of the airframe would have to be milled out of a solid block of aluminum that is at least three inches thick, wide enough, and long enough to set the proposed piece in. Milling such a piece requires a great deal of time that could be completely wasted if there is a flaw in the metal block or the milling machine departs from its planned path. Casting can also require a great deal of machining if the part is not in its final shape. Industry is developing a process known as near net casting that greatly reduces machining and waste, but it is not widely used yet. Once the basic parts are fabricated, they must be assembled.

Assembly costs for aluminum can vary significantly from composite material parts. A composite panel that is cocured with ribs and supports can be made without riveting which is an expensive process (17:vol.1,p.9-44). A comparable metal part would require each rib and support to be riveted to the main skin. Riveting requires holes be drilled and the parts aligned before the rivet can be installed and bucked. On large parts, the difference in assembly time can be significant. There are two methods of estimating the cost of constructing aluminum airframes.

The first method is to use the ICAM Manufacturing Cost/Design Guide (12). ICAM is the Air Force Wright Aeronautical Laboratories Materials Laboratory's Integrated Computer Aided Manufacturing (ICAM) program. Battelle's Columbus Laboratories (BCL) developed the guide for the Air Force under contract number AFWAL-TR-83-4033. The guide enables an engineer to find what the industry average cost for fabrication and assembly of airframe parts would be. The guide was developed by having aerospace industry corporations track the labor hour and tooling costs of their manufacturing processes for the types of structures that are used in airframes. The values were then averaged and presented as curves that measured size against labor hours or tooling hours. Additional curves are provided for assembly of the smaller parts into useable parts such as spars or ribbed panels (12). The raw data that was used to

build the curves is not available because the contract specifically states that the information supplied by contractors will not be given to the government or to competitors (12:vol.1,p.4.3-41). Considering the low level at which cost estimation is accomplished in the model, the method would be extremely inefficient in predicting the cost of entire airframes because every part must be developed and then assembled, but it is useful in examining cost impacts of various design decisions. The most useful aspect of the model for this thesis is its ability to predict the cost of small parts and subassemblies just as the FACET model does for composite material. Individual parts can be designed and evaluated on both models to develop costs for comparison.

The second method used to determine costs of airframes is parametric modelling such as DAPCA III and other models. The parametric airframe models that are available should be examined and compared to DAPCA III to determine if it is the most appropriate choice for modification.

Parametric Airframe Cost Models

There are several parametric airframe cost models in use today. Joseph P. Large and K.M.S. Gillespie (11) reviewed all of the most significant models in 1977. Their evaluation included a description of what parameters the models estimated, what data they used, what inputs were required and a measure of each model's success in predicting

development and production costs for recently built aircraft with known costs. They reviewed the Rand Corporation DAPCA model, versions I, II, and III, the Planning and Research Corporation (PRC) model, the Science Applications Incorporated (SAI) model and the J. Watson Noah (JWN) model, versions I and II. The first parametric models reviewed were the DAPCA models. The DAPCA models are an evolution of a single model and data base rather than independent models. DAPCA III is the latest Rand model and will be the only one discussed.

DAPCA III Model. The DAPCA III model uses only two independent variables to determine cost. They are maximum speed at best altitude and AMPR weight. Given these two inputs, DAPCA III produces the total airframe costs broken down into the following cost elements (2:6):

DAPCA III COST ELEMENTS

Development:

Total engineering for flight-test aircraft
Total tooling for flight-test aircraft
Nonrecurring manufacturing labor
Recurring manufacturing labor for flight-test aircraft
Quality control
Nonrecurring manufacturing materials
Recurring manufacturing materials for flight-test aircraft
Flight test

Procurement:

Total engineering for production aircraft
Total tooling for production aircraft
Recurring manufacturing labor for production aircraft
Recurring manufacturing materials for production aircraft
Quality control for production aircraft

Figure 2

Whenever possible, the output is expressed in labor hours charged to the government for each cost element, thus avoiding the problem of comparing dollar costs for different years and wage scales. The only output that is expressed in dollars is the materials required, which are expressed in 1975 dollars. Airframe material costs for all aircraft in the data base were indexed to 1975 dollars using methods derived from Aerospace Price Indices, Rand Report R-568-PR (10:131). By limiting the use of indices, Rand hoped to eliminate as much of the error associated with them as possible. The cost estimating relationships (CERs) used in regressing the data were based on a logarithm-linear relationship as it provided the best distribution of the residual error terms while logically representating the data (10:17). The equations are measuring relative error instead of actual error.

Rand Data Base. The Rand corporation has been massing airframe cost information in some form since 1947. The data base has been updated several times to expand its applications. In each case, the goal of the Rand data base was to be "representative of the costs to be expected in a program with its fair share of problems but with no major design changes" (10:7). This has been accomplished by going to the companies that produced the airframes and using their data when government data was not available. To keep the problem of different labor costs out of the data base, they

have centered on labor hours that were charged to the government whenever possible. The logic in that was that labor pay rates vary as much as 30 percent between companies so using labor costs would be less accurate (12:41). Using the number of hours charged to the government reflects the amount the government paid for the program. The data base has been periodically indexed to reflect more modern material costs. The current material costs are expressed in 1975 dollars. The adjustments were made to the data base using the specialized airframe industry indices instead of those common to the day to day living like the consumer price index. The original data was normalized to reflect all costs in 1973 dollars, making that the base year. The methodology for developing index numbers for each year after 1973 is readily available so complete modification of the data base is not required. The Rand data base was indexed to 1975 for the DAPCA III model. The following 25 aircraft are currently used in the data base:

RAND CORPORATION DATA BASE

A-3	C-133	F-14
A-4	KC-135	F-6
A-5	C-141	F-100
A-6	C-5A	F-102
A-7	C-130	F-104
B-52	F-4	F-105
B-58	F-3	F-106
RB-66	F-111	T-38
		T-39

Figure 3

Aircraft with flight dates prior to 1952 were dropped from

the data base to both update the data sample and eliminate data collection problems on the older aircraft. The broad spectrum of aircraft makes the data base usable for predicting a wider range of aircraft. For example, the B-1B is as fast as a fighter but weighs as much as a bomber. Neither a data base of fighters or one of bombers could produce a reasonable estimate, but together, the speed of the fighters and the weight of the bombers and cargo aircraft combine to produce a better estimate. Aircraft model changes were only accounted for when they caused a significant increase in the labor hours required to produce the new model (10:7). Additionally, in specific cases, certain outliers in the data base were eliminated after consultation with the contractors. The result is a data base that is not perfect, but compares favorably to others in the field.

J. Watson Noah Models. The J. Watson Noah models use much of the Rand cost data (3:A-3); however, they have added two additional independent variables, a ratio of gross takeoff weight to AMPR weight and a dummy variable to account for complexity. The dummy variable serves as a means of indexing the cost of technology advancements. It is used when the engineers consider the proposed aircraft to represent an advancement in the state of the art. The logic in this is that new ideas take longer to develop and have unforeseen costs. Historical examples like the C-5A (first

wide-body, super heavy-lift) and the F-111 (first swing-wing and supersonic low altitude penetration) tend to lend credibility to the idea. Large and Gillesepie (11:31) see some problems with the development of the index. First, they question some of the aircraft selected to represent state of the art advances; including the F-102 follow-on, the F-106 and excluding the first swept-wing jet bomber, the B-47, to name two examples. Second, they question the weighting of the index. The decision to use the index can as much as double the airframe cost in some cases. They also see problems with the gross takeoff weight/AMPR weight ratio parameter for compact aircraft like the T-38 or aircraft with excessive external stores capacity like the B-58. Additionally, there is a statistical problem with the use of the ratio variable in that it is correlated to the AMPR weight. The output of the JWN models does not lend itself to easy comparison with the output from the FACET model in that costs are expressed as total costs, recurring and nonrecurring only. Still, the JWN models performed better than any other statistical model when used to predict the cost of recently constructed aircraft, provided the complexity factor was used correctly. Large and others (10:pp.44-45) attempted to evaluate the probability of consistently correctly choosing whether to use a complexity factor or not by polling two engineers for their opinions about program complexity. The engineers were asked to rate

14 aircraft programs as having either minimum, some or many problems during development and production. They agreed on 8 of 14, barely half of the aircraft, were one category apart on 5 aircraft and at opposite ends of the spectrum on the other aircraft. From this limited survey, Large and others (11:44) concluded that the probability of correctly identifying the need for a complexity factory is not good for one estimator but might be improved with a careful survey technique.

JWN Data Base. The JWN models all use the cost information as it was amassed in the Rand data base, but with use different performance characteristics. The most significant problem with the JWN performance characteristics is the use of gross takeoff weight for the primary mission. Many aircraft have been modified several times over to change their primary mission, additionally, aircraft designed as multi-mission aircraft like the F-111 and the F-4 have several mission profiles and must be able to handle the heaviest takeoff weight regardless of whether that is the one that JWN II uses. Still it is a reasonably sound data base.

Planning Research Corporation. The third model discussed is the PRC model, developed in 1967. The PRC model has made contributions to the improvement of cost estimating by trying to account for acquisition management as a possible influence in the cost of programs. The model

uses inputs from four general categories, program characteristics, aircraft characteristics, contractor characteristics, and a time element: year of first delivery. Program characteristics include the responsible agency, Air Force or Navy, lot quantity, delivery rate and an estimate of the airframe weight growth. These independent variables have been designed to capture the management induced costs. Airframe weight growth is included in this area because it reflects the amount of modifications made to the airframe during production. The aircraft characteristics are speed, altitude and weight, both AMPR and aircraft empty weight. Speed is entered twice: speed at best altitude and speed at sea level expressed in mach number. The contractor data has been included to try and account for differences in individual firm's accounting practices. The measure is needed because much of the data base is in dollars. The aircraft used for the data base were first flown between 1945 and 1958; only the early century series aircraft were included. Large and Gillespie conclude their analysis by evaluating several 1960s aircraft and showing that the model underestimates small aircraft and overestimates large aircraft, but as a whole does fairly well, given the data base (11:27). For the purposes of this thesis, the model is not usable because it requires contractor data that is not available at the earliest stages of planning.

PRC Data Base. The PRC model data base, as previously noted, contains aircraft from the 1950s and 1940s. The bulk of the aircraft in the sample are all-aluminum with a minimum of steel or titanium. The inclusion of a time of delivery factor requires a base year to project from. If the base year is changed, the final equations change. The first flight factor was developed by counting the number of quarters from 1940 that it took to make the first flight. Rand uses this approach in its jet engine model with 1942 as the base year because it was the year the first American jet engine was developed, but found that it wasn't statistically significant in the DAPCA III model and actually degraded the final estimates compared to actual costs (12:14). The foremost problem with the PRC data base is that the values are all in dollars with the inherent disadvantages previously discussed (11:20).

Science Applications Incorporated. The most specialized model is the SAI model for cargo aircraft. The model is intended to estimate the production cost for cargo aircraft in the conceptual stages of development. The only input variable used is weight. The cost elements are broken down by airframe sections: wing, tail, et cetera and subsystems: avionics, electrical systems, airconditioning, et cetera. This thesis finds the model unsuited for modification to cost composite material because the model has limited use.

SAI Data Base. The SAI data base includes military and civilian transport aircraft. All costs are expressed in 1975 dollars. The most unique aspect of the data base is that it is organized by aircraft systems. Each system may have different aircraft in it or none at all (11:38). The pneumatics system data are determined by using the subcontractor directly ()12:39).

MLCCM Model. Since Large and Gillespie made their review of available cost models in 1977, a new model has been developed by the Grumman Corporation under contract from the Air Force Flight Dynamics Laboratory. It is the Modular Life Cycle Cost Model (MLCCM), technical report AFFDL-TR-78-40 (5). Its goal is to provide "the design engineer with the tool and capability to optimize design/performance/cost across the life cycle structure" (5:1). The first two modules are Research Development Test & Evaluation, (RDT&E) and Production. They can be estimated separately or together with the other modules which are Initial Support Costs and Operational Support Costs. The model estimates the airframe cost as well as engines, avionics, et cetera, to provide a flyaway cost. The CERs were developed to conform to a work breakdown structure format to provide visibility to the subsystems in each design. The criteria for selecting estimating parameters were engineering logic and statistical significance; the first and second derivatives for the parameters had to

logically follow cost. For example, if the change in the magnitude of a variable did not result in a logical change in cost, it was not used regardless of how statistically significant it appeared to be. Like the Rand DAPCA model, labor hours were used where possible and 1975 dollars were used everywhere else. There are some problems in comparing DAPCA to MLCCM. The airframe costs are computed using very specific design parameters such as wing thickness/chord ratio, wing area, fuselage wetted area (internal fuel capacity) and speed. While most of The parameters are known early on, they still require some detailed engineering or a default value before an estimate can be accurately developed. The parameters used in determining the RDT&E costs have similar limitations. They include ultimate load limit, maximum mach speed, maximum gross weight, total wetted area, and the number of prototype aircraft. Ultimate load limit is the amount of "g" forces the aircraft can sustain, which differentiates between types (cargo versus fighter) as well as indicates the amount of design work and structural strength required. Total wetted area is a measure of aircraft volume which affects drag and structural design. Maximum speed, when combined with load limit differentiates between fighter and attack aircraft, as well as indicating the design effort required.

The model has an outstanding feature in that it contains an index for modifying estimates to account for

composite airframes. The MLCCM model develops cost factors for each of the main sections of an aircraft, wing, fuselage/nacelle (NACL), and tail. The cost factors are labor, tooling, and materials. The base for the index is aluminum and the base year, 1986, is a projected estimate of the costs given estimates of proposed manufacturing technology (5:vol.1,74). The index is shown in Table 1.

MLCCM 1986 STRUCTURAL MATERIAL COST FACTORS

		Factor					
Material		Al(ref)	Ti	Stl	Kevlar	Graphite	Boron
Structure							
	Labor	1.00	.99	1.75	.85	.75	1.24
WING	Tooling	1.00	1.98	1.53	1.38	1.73	1.73
	Mat'l	1.00	2.65	.79	2.13	3.02	11.45
	Labor	1.00	.82	1.72	.95	.86	1.25
BODY &	Tooling	1.00	2.10	1.60	1.38	1.73	1.73
NCLS	Mat'l	1.00	2.46	.87	2.44	3.45	13.10
	Labor	1.00	1.37	1.64	.95	.89	1.27
TAIL	Tooling	1.00	1.74	1.41	1.38	1.73	1.73
	Mat'l	1.00	2.64	.80	2.18	3.09	11.73

Table 1

The values shown reflect advanced manufacturing methods such as robotics and automated machines. It was developed by polling industry experts in production and materials for their opinion. The values represent the average value of the opinions as gathered in 1980. The first step in using the index is to determine the cost of an all-aluminum airframe and then multiply that value (CER-Al) by the appropriate percentages of each different material and the

index for that material. That value is the correction factor which should be added to the original all-aluminum estimate to get a final cost. For example, if the aircraft is 40 percent graphite and the remainder aluminum then the cost would be the cost of an all aluminum aircraft (CER-Al) times (.40) times the graphite column plus the (CER-Al). The only step this method had eliminated is the separate CER for a composite part. Decamp and Johnson (4) tested the MLCCM model on the F-15, F-16, and AV-8B. They treated the aircraft as all-aluminum aircraft and then reran the program with the proper metal mix inputs. They compared these estimates with a DAPCA III estimate and a DAPCA III estimate multiplied by a single complexity index number. The MLCCM estimates were within 1 to 3 percent of each other on all three aircraft and very close to the DAPCA III estimates. Their conclusion was as follows (4:A-8):

> It can be seen that the scatter of the original aircraft data with weight used in the Rand study is such that any of the lines could reasonably describe a costing trend. Hence no clear trend of manhour difference based on materials is observed.

The actual cost of the three aircraft were not compared to the estimated costs that the models used in the study developed. The MLCCM model does do a reasonable job of estimating costs; however, it does have some weaknesses. First, it does not predict the cost of bomber type aircraft. The data base consists of fighter or cargo type aircraft. Second, the data input are engineering specifications such

as wing chord or wetted area.

However, the MLCCM materials index can provide an additional point of reference for the index developed in this thesis.

MLCCM Data Base. The MLCCM data base has been discussed thoroughly. Its greatest advantage is the inclusion of different materials. The greatest disadvantage of the MLCCM data base is the exclusion of bomber aircraft from the data base which reduces the predictive power of the model in that area.

Conclusions

The Rand DAPCA III model is the most general model available and demonstrates the greatest flexibility in predicting airframe costs in the earliest stages of program development. Given the above conditions, the DAPCA III is the logical choice for continued development. It predicts over a wider range, at the earliest stages of development, and it is more parsimonious. The associated data base is also the best available basis for parametric estimation. For these reasons, the index for composite materials will be in a format that is compatable with the DAPCA III output.

CHAPTER III

METHODOLOGY

Introduction

Modifying the output to the DAPCA III model so it accurately represents the cost of composite material is a multi-step process. The first step, a review of the literature, produced only one plausible approach: modifying the total cost for a metal aircraft by an index factor that reflects the differences in labor and material cost inputs caused by composites. The second step is to collect the necessary metal parts data for conversion to composite material using FACET. The third step will be to compare the parts and develop the index. The final step will be to validate the significance and accuracy of the resulting index. A methodology for the process is needed.

Data Collection

The objective in collecting data for this thesis will be to get the most accurate information possible. Obtaining actual cost data for individual parts is extremely difficult because industry rarely assigns actual costs to each part, but instead assigns it to assemblies. Part information is needed to generalize the results from the indices. If all of the assemblies come from fighter type aircraft, the applicability to large bombers and cargo aircraft would be questionable. Some individual parts that could be used in any aircraft are needed to be able to generalize the results. However, there is also a need for some assemblies

to differentiate the assembly costs for metal and composite construction. If some larger parts are not used, the assembly cost advantages would not be captured and would have to be estimated. Mr. Stan Nisevich, ASD Cost Research Branch expert for composite material, considers the assembly costs to be crucial in any composite material to metal comparison (13). The metal part descriptions and cost data will be captured using the *ICAM Manufacturing Cost/Design Guide*.

The *ICAM Materials Cost/Design Guide* curves provide some of the same information that the FACET model provides: recurring labor hours and tooling costs (12). The smaller parts that will be designed with it will be such items as access panels, ribs, skins, spars, and stress panels that require some assembly. The larger parts will be sections of fuselage, wing, and control surfaces such as ailerons and rudders. A variety of aluminum construction processes will be used to reflect the different methods of providing different engineering qualities to the parts. For example, the machined bulkhead is thicker and more rigid than an assembly of several different sheet metal parts formed into a bulkhead. Composite materials that replace metal parts must have the same or better engineering qualities. Using different metal parts and then designing the same part out of composite material will help to increase the validity of the results. Using the ICAM model has two major

shortcomings: the model does not provide any material cost and it uses dollars to predict the cost of forgings, castings and extrusions.

To develop the recurring material costs, the final weight of the part will be multiplied by the inverse of the usage rate for that particular process. A usage rate measures the difference between the material that is present at the start of the process compared to the amount of material in the final product. For example, a rate of .25 means only 25 percent of the material present at the start the process was in the final product. Thus if a part had a usage rate of .25 in its construction, its weight would be multiplied by 1/.25 or 4 to get the material used in the part. The factors that will be used are shown below in table 2.

<u>MATERIAL USAGE RATE</u>

aluminum plate	.25
aluminum bar	.25
aluminum casting	.90
aluminum extrusions	.65
aluminum forgings	.25
aluminum honeycomb core	.85
aluminum sheet	.50

Table 2

These values are the specific rates for a particular company, but have been presented as representative of the rates for the industry (7:A.41).

The second problem with ICAM is in developing manhour estimates for forgings, castings, and extrusions. They will

be determined by dividing the dollar figure provided by a representative industry rate of 50 dollars an hour to determine the manhours used in developing the part. Fifty dollars was chosen because the ICAM Materials Cost/Design Guide recommends 50 dollars as a representative "wrap rate (12:p.4.5-8)." A wrap rate is the dollar value that a company charges for every hour of labor. The rate has all of the corporate overhead costs wrapped up in it as well as material and labor, hence the name wrap rate. Using a wrap rate value is reasonable because the parts are usually purchased parts for most aerospace corporations. Once the metal parts have been developed and their values estimated, they can be redesigned as composite parts so FACET can be used to estimate a comparison value.

The design of the complex parts will be based on simplified designs of parts from a wide variety of aircraft. Their basic structure will be taken from past experiments in converting metal parts to composite parts. Using this approach will ensure that the metal parts can be made into composite parts. There is no need to fully design the parts beyond their basic structure because the same fittings and attachments would be used on both the metal and the composite material airframe. The relative strength of each metal part and comparable composite part must be both equal and realistic. The realistic strength of each part can be achieved by copying metal thickness specifications and

distance between spars from comparable engineering drawings for each part. When there is any doubt as to the strength of a part, the design will be over-specified. Achieving comparable strength in the composite parts will be done through the number of plies in the part. The Wright Aeronautical Laboratories Flight Dynamics Laboratory Group Leader for Structures Preliminary Design (AFWAL/FIBC), Cecil D. Wallace, recommended the following relationships between metal thickness and the number of plies be followed for the parts to have comparable strength (18):

METAL THICKNESS TO COMPOSITE PLY RELATIONSHIPS

1) For wing and tail skins: 1.48 X (TM/TP)

2) For fuselage skins: 1.61 X (TM/TP)

3) For substructure: 1.20 X (TM/TP)

TM = thickness of metal
TP = thickness of a unidirectional graphite epoxy ply
The factors were determined by comparing the shear strengths of each material.

Figure 4

The relationships are based on the premise that composite parts are a minimum of 15 percent lighter than comparable metal parts (18).

According to Mr. Harry S. Reinert, graphite plies vary in thickness from .005 to .008 inches with .006 being the most common (16). The above formulas will be used with (TP = .006) to determine the number of plies required to make a composite part comparable to metal. For example, a metal rib (substructure) that is .063 inches thick would result in

a composite part that is:

1.20 X (.063/.006) = 10.5 plies thick.

This thesis will have the number of plies used rounded up as a safety factor. Once the metal parts and composite parts have been constructed, they can be used to develop an index for modifying the DAPCA III model.

Methodology for Modification

This thesis will use the internal adjustment factors available in the DAPCA III model as a basis for a composite materials index. The computer program for the DAPCA III model allows adjustments to the following variables (2:63):

tooling hours
engineering hours
nonrecurring manufacturing labor hours
recurring manufacturing labor hours
nonrecurring material costs
recurring material costs
flight-test cost

A direct relationship between material content of an airframe and the changes in labor hours and material costs is logical, but the exact relationship is not readily apparent. Adjustments can be made in several ways. The method most often used in the past has been a search for an "expert opinion" as to what the new factor should be, given what is known about the quantity and type of material to be used in the subject aircraft. Expert opinion can be gathered many ways: with a Delphi approach, through group discussion, or averaging a survey of opinions, to name a few. The values for composites used in adjusting the MLCCM

are opinions which provided reasonable results (4:A-8). Rather than develop an "expert opinion," this thesis will use a second method to develop an index.

The ICAM Manufacturing Cost/Design Guide will be used to estimate the cost of 30 aircraft parts that are representative of parts found in the entire spectrum of aircraft from bombers to fighters to cargo. The FACET composite material cost estimating program will provide the cost of the comparable parts made out of composite material. The FACET cost estimates will be divided by the ICAM cost estimates to provide data for developing an index. The index will be applied to the DAPCA III model to adjust airframe cost at various percentages of composite material. The index values will be expressed as composite material/aluminum ratios for the following inputs:

recurring manufacturing labor hours
recurring materials cost
tooling

A default value of 1.0 will be used for flight-test costs, nonrecurring costs, and engineering costs. The flight-test, nonrecurring manufacturing manhours, and nonrecurring material dollar values are left at 1.0 because FACET does not provide those costs. The engineering hours for composite material will be left at 1.00 because there is little indication that they are significantly different from the hours required for metal (9:8). Tooling costs will be estimated by comparing tooling hours generated by the ICAM

model to setup hours used in FACET. The tooling costs that are being captured are not the costs of purchasing machinery to do the job, but the manhour cost of preparing the machinery, developing jigs and special equipment needed to do the job (14). To provide complete flexibility to the user, the index must be able to correct the DAPCA III model over a wide range of composite material options. There are several problems in creating that flexibility.

Index Development

Current investigations show that the hour and cost ratios of composite material to aluminum vary according to the complexity of the part being fabricated and the manufacturing method used (7:A-36). Complex composite parts can require more fabrication costs than simple parts; however, they can have significantly lower assembly costs that more than offset the difference. As the amount of composites in the airframe increases, the ratio of complex to simple parts varies. It is possible an aircraft that is 10 percent composite material could vary in composites distribution from a single component like a test composite wing box structure to only non stress-bearing panels and fairings. At 20 percent composite material, the number of complex parts would most likely increase and at higher percentages, it would not be possible to avoid them. To allow the analyst the opportunity to develop a mix of complex to simple parts as necessary, an index number for

complex parts and an index number for simple parts will be developed. The parts will be considered complex if the composite version requires assembly other than cocuring. For example, a panel or a stringer can be completed in one curing operation as can a complicated I-beam structure, but a wing box or aileron requires more than one curing operation to create the part. To use the index numbers, the estimator need only determine what mix of composite parts is expected in the new aircraft. A default ratio for each composite percentage is provided. The default values are based on current uses and planned designs for future aircraft. The 10 percent value will be 90 percent simple reflecting few assembly benefits from limited composite material application and decrease to 30 percent simple parts as the use of composites is increased. The logic in such a low percentage is that many of the original simple parts will be incorporated into the complex parts by cocuring methods. The only remaining simple parts would be some access panels and sections of the wing surfaces that are attached in a traditional manner to allow maintenance access to wiring.

A second problem with the index is the cost ratios for composite material to aluminum are effected by the differences in fabrication and assembly methods. If either the aluminum manufacturing method or the composite manufacturing method changes, the index numbers could

change. To address this, all of the composite parts will be made from one material, graphite/epoxy which is the most common material in use (17: vol 2 A-20), and a core method of composite material manufacturing will be used. The method shown in table 3 represents the average capability of the industry today (16).

COMPOSITE FABRICATION PROCESS

STEP	PROCESS
material used	graphite/epoxy
material dispensing	automatic
ply cutting	Gerber blade
lay-up	Automatic tape layer
debulk	cold
bagging	no bleeder-reusable
debulk	none
bagging	bleeder-resusable
curing	autoclave
finishing	as required

Table 3

Since debulk and bagging methods vary significantly throughout the industry, the two most common methods have been included and will be used alternately. When it is required for both the metal and the composite parts, additional steps will be added such as trimming. Using an average method will be compatable with the metal manufacturing methods which represent average industry labor and tooling time. The different aluminum fabrication methods must be used because they are required to impart the desired engineering characteristics to the part. Since the labor curves for each process represent industry averages, different methods of each specific fabrication process are

accounted for. Having addressed the two greatest influences to the index, it is now possible to address the actual method of developing the index numbers.

An index number is used to provide a value useful for comparing magnitudes of related items (8:630). It is expressed as a unitless ratio. Several considerations must be made when developing index numbers. The most obvious is that each number used to compute the index should have the same meaning or relationship compared to some base item. The cost of the hundredth part does not have the same meaning as the cost of the first part constructed; they should not be compared to each other because they do not come from equal backgrounds. Additionally, the parts must have a base of comparison (8:632). This index will be based on the first unit cost of manufacturing an aluminum airframe. The cost of aluminum will be 1.00 and the relationship of composites to that cost will be expressed as a percentage of that cost. Therefore, all of the parts will be expressed in cost of the first unit produced and aluminum will be in the denominator.

The second consideration in developing an index number is the selection of type: simple, relative, or weighted. A simple index number is the sum of the values for the modifying variable (composite material) divided by the sum of the values for the base variable (aluminum). A simple index can be used if all of the variables in the index have

the same units of measure and relationship to the base. If all of the variables do not have the same units of measure or relationship to the base, then a relative index should be used. A relative index takes each paired set of variables (an aluminum wing and a composite wing) and develops a unitless ratio for each observation. The ratios are then summed and divided by the total number of paired variables to get an average index . As an example, if the data collected had some sample points for the 200th part built and some for the first part built, a relative index approach would be appropriate. However, all of the parts used in developing the thesis index numbers will be for the first unit value. The last method of developing an index is weighting the variables. A weighted index gives some of the observations of the relationship between the variables more weight than the others to account for their greater influence (8:635). The final index used in this thesis will be a result of all three approaches to index numbers. The two initial index numbers for simple and complex parts will be obtained using a simple index approach. The sum of the values for the complex composite parts will be divided by the sum of the values for the complex aluminum parts for each specific index, nonrecurring tooling costs (NRTC), recurring manufacturing manhours (RMM/H) and material costs (MAT'L). Applying the two index numbers to the DAPCA III model will require a ratio of complex to simple parts, a

relative index number. The proportions of the two values will be weighted according to how the percentage of composites in the airframe varies. The basic index will have the following format:

<u>COMPOSITE MATERIAL INDEX FORMAT</u>

SIMPLE INDEX NUMBERS		DEFAULT VALUES			
SIMPLE PART (A)	COMPLEX PART (B)	PERCENT COMPOSITE	PERCENT COMPLEX	INDEX VALUE	ADJUSTMENT FACTOR
X.XXX	X.XXX	10	10(B1)	X.XXX	X.XXX
		15	20	X.XXX	X.XXX
		20	30	X.XXX	X.XXX
		25	40	X.XXX	X.XXX
		30	50	X.XXX	X.XXX
		35	60	X.XXX	X.XXX
		40	70	X.XXX	X.XXX

Figure 5

To correct the DAPCA III estimate, the analyst would estimate the percentage of composite material in the airframe, then estimate the percentage of complex parts or use the default values. The complex part index (B1) would be multiplied by the chosen complex part index (B) and the simple structure index would be multiplied by (1 - complex percentage). The resulting two values would be summed to give the composite material index value:

INDEX VALUE = (B) (B1) + (A) (1-B1)

Each of the three cost elements (NRTC RMM/H, MAT'L) have index values. To determine the impact on a DAPCA III estimate, the analyst would multiply the index value by the percentage of composites in the airframe to get the adjustment factor. The adjustment factor would then be

applied to the DAPCA III estimate as shown below:

(1- percent composite) + (percent composite X adj. factor)

For example, if an aircraft was 30 percent composite material and had an index value of (.88), then the value of that particular adjustment factor would be:

(1.00 - .30) + (.30 X .88) = 0.964 adjustment factor

The validity of the index and hence the adjustments rests on the accuracy of the input data, the accuracy of the two cost estimating models, and the proper explanation of assembly cost benefits through complex part percentage choices. The indices must be tested to enable the analyst to use them with confidence.

Validation Methodology

Validating the model, in the sense of comparing model estimates to the unmodified DAPCA III estimates and to the actual costs will be difficult. There are no actual airframes with large composite material percentages to compare the two models against. Comparing the adjusted model performance and the unadjusted model performance with aircraft that have a small percentage of composites is possible, but the results will be misleading because the early aircraft all used more labor-intensive methods of production than this model assumes. Still, some improvement over DAPCA III should be evident. The most useful approach to validity would be to demonstrate areas where the model is definitely inaccurate through sensitivity analysis.

Sensitivity analysis can be done to see the extent data variations and composite mix changes effect the cost estimate. Data variations effect the simple and complex index values.

The first sensitivity test evaluates which parts have the greatest relative change in cost when transformed from aluminum to composites material. The first step is to eliminate the three greatest ratios from each complex part index and the four greatest ratios from each simple part index and recompute the index value. The second step is to eliminate the three smallest ratios from each complex part index and the four smallest ratios from each simple part index and recompute the index values.

The second sensitivity test examines which parts have the greatest impact on the composite part index values and therefore DAPCA III. The same process used in test two is repeated except the greatest and least differences are chosen instead of the ratios.

The two tests can be examined to determine if there is any single factor could cause parts to be both expensive (greatest numerical difference) and less efficient (largest ratio). Finally, once the new values have been determined for both tests, they can be applied to the default composite mix values to determine a range of possible influences on DAPCA III.

CHAPTER IV

INDEX PREPARATION AND ANALYSIS

Data Modification

The ICAM manual and FACET computer program successuflly provided the raw data for developing the indices. Before the indices could be developed, several adjustments to the data were necessary.

Standard hours. The first adjustment was generated by the fact that both the FACET model and the ICAM manual provided their output in standard hours. Standard hours are defined by the ICAM manual as "the industrial engineering base standard hours (IEBSH) to perform a specific factory task, operation, or work elements (SIC)(12:p.2-13)." No specific industrial engineering method was used to determine the standard hours, rather the hours represented in the ICAM manual are an industry average of standard hours collected by various means. Standard hours represent only the time necessary to perform a specific function and omit time for necessary collateral activity and the human factor. To capture all of the costs for both metal parts and composite parts, their respective standard hours had to be adjusted with a realization factor. If composite material and metal working processes used the same realization factor no correction would have been necessary; however, there were significant differences. The FACET model relied on three

separate realization factors in developing the total cost of manufacturing a composite part. Those manufacturing processes that were primarily manual labor used a realization factor of 18, those that were machine oriented used a 7.6 realization factor, and those that were automatic or robotic used a realization factor of 2. These realization factors were obtained from Mr. Ray Paner, Northrop Corporation Cost Analyst and author of the FACET algorithms (14). Thus, a standard hour of FACET time could represent anywhere from 2 to 18 hours of actual time required to build a part. A more vexing problem developed in determining the variance to use with the ICAM manual because the manual specifically left that value up to the user. Mr. Stan Nisevich polled cost analysts at several major aerospace contractors for a representative aluminum parts manufacturing realization factor. The modal value of 7.5 was selected for the thesis metal process realization factor because it closely agreed with the FACET model value of 7.6 for semi-automated machine work, the prime method of making metal parts, and because the corporations that had realization factors far from that value also had radically different production processes. One corporation used a variance of 4.2, but that corporation was nearly entirely automated. Another corporation was greater than 7.5, but that company used manual labor extensively (13). The final problem with the ICAM manual data was that it was expressed

in terms of 200 units produced instead of the first unit. Correcting the data required the use of learning curve theory.

Learning curves. The learning curve theory is based on an observation by T. P. Wilson in a 1936 article "Factors Affecting the Cost of Airplanes," *Journal of the Aeronautical Sciences*, Vol 3, February, 1936 (1:2), that as a worker repeats a task, the worker performs the task faster and more efficiently. The most common applications of the theory state that each time the quantity produced doubles, the time to produce the doubled unit decreases by a constant percentage. The amount of decrease is described as the learning that has taken place and is expressed as a percentage value. Thus, if a worker takes 100 hours to perform a task for the first time and only 90 hours the second time, learning is occurring at a 90 percent rate (slope). What is actually happening is the worker is failing to learn 90 percent of the task each time, but is learning 10 percent of the task every time. The theory implies that if the worker performed a task an infinte number of times (units), the worker would learn all there is to know about performing the task, and the time it would take the worker to perform the task would be reduced to zero (1:3). The learning phenomenon can be applied to more than just the worker (1:3). Management also learns to be more efficient and provide materials to improve production

methods as well. The learning curve theory has been applied to both the ICAM manual and the FACET program as a means of more accurately representing the cost of producing airframes.

The FACET model used fixed learning curves for manual labor, semi-automatic machining and automatic/robotic machining. According to Mr. Paner,it assumes that manual labor moves down a 78 percent slope, semi-automatic machining improves on a 85 percent slope, and automatic/robotic machining improves on a 95 percent slope (14). The lower the number, 78 percent versus 85 percent as an example, the greater the learning or improvement. FACET can generate up to ten different unit cost values depending on the specified unit of production. Each computer run used in this thesis specified the cost of producing the first unit. Selecting the first unit option allowed the model to reflect the cost of the nonrecurring tooling costs (NRTC) more accurately because the costs were all assigned to one unit instead of being allocated to several. The ICAM manual provided the cost of the 200th part instead of the first unit (12:p.1-10).

To be able to compare the metal part values to the composite part values, they both had to be adjusted to the same unit. FACET could have been adjusted to unit 200 very easily, but then the nonrecurring tooling costs would have been very difficult to predict and the objective of

modifying DAPCA III to predict the first unit cost of a composite material aircraft would not be met. The nonrecurring tooling costs are affected by the number of parts made in each lot or run since they are only incurred once for each run. Using a value other than unit one would have meant establishing a production rate that was the same as the one reflected in the ICAM model, which is unknown. Instead, it was easier to modify the ICAM model values to reflect the unit one cost. Like FACET, ICAM has different learning curves for different functions. Unlike FACET, the curves are not based on three broad categories but rather specific manufacturing processes (12:Table 3-1). Sheet metal operations use a 90 percent slope for determining the values of units produced in the future. The ICAM model also provides a learning curve value that applies to different assembly methods; this thesis used the 85 percent slope for floor assembly (12:Table 3-1). Applying the learning curve corrections allowed the manhour values for composites and metal to be compared directly. Comparing the material used in each part also required adjustments.

Material cost. The material costs provided by FACET were extremely optimistic. According to Mr. Paner, because the process was automated, anytime that the dimensions of the material being used was a multiple of the dimension of the part, FACET assumed "perfect nesting" of the parts so that no material was wasted. The result was that in many

cases, there was a 100 percent usage rate for the material. To correct for the problem the part material area was computed and then an 80 percent usage factor was applied to it to get a gross material required. The 80 percent figure approximates an industry average (14). The adjustment process was also applied to parts that didn't suffer from perfect nesting problems. Adjusting all of the values with an 80 percent factor provided internal consistency and precluded the possibility of having an unknown bias introduced to the data. The usage rates in Table 4 were applied to the different metal components. Once the pounds of material used were adjusted, they were multiplied by the dollar price per pound to determine a dollar cost. The costs used were as follows:

Composite material = 30 dollars/pound

Aluminum metal = 4.51 dollars/pound

The material costs are representative of the current market rates for an economical order (13).

Data Presentation

Data were collected on 10 large assemblies and 20 smaller panels, subassemblies and substructure. Each design choice was made to achieve a representative sample of the types of composite and metal construction found in aircraft. The complex part sample contains three fuselage sections, three control surfaces, three wing components and a cargo door. The cargo door is proportional to the types of parts

found in aircraft because it is comparable to a bomb bay door, which would have the same construction and stress requirements. The simple part sample met the same criteria. A large number of stringers and stiffeners were included here even though none of the composite material assemblies used them. The assemblies used a corrogated skin cocured to the underside of the normal skin that acted like a continuous series of stiffeners. The stiffeners and stringers were weighted so heavily in the simple index number for three reasons. First, composite stiffeners are being added to metal parts as lightweight strengthening modifications for older aircraft. Second, composite parts are also being used in composite airframes where corrogated surfaces or Kevlar honeycomb are not practical. Third, they represent a significant percentage of the simple parts in metal airframes. In addition to selecting a representative sample of parts, a representative sample of manufacturing processes were used. Different processes for the same part often produced different cost even though the dimensions of the parts were identical. In a few instances, either a composite part or a metal part was entered into the index twice to show the impact of a process used in the opposite material. This was most obvious in the smaller parts, but parts one and two, fuselage sections, are identical for comparison to two radically different aluminum processes.

The parts are presented with name, dimensions in

inches, and general shape followed by a brief description of the process used for each part and the method of assembly. Following the presentation of the parts, the three indices for modifying DAPCA III are presented: Table 4, Nonrecurring Tooling Manhour Cost, Table 5, Recurring Manufacturing Manhours, and Table 6, Material Dollar Cost.

Complex Parts

Part 1: curved fuselage section 36 X 96

Composite: 36 ply skin cocured with 24 ply substructure. Four ribs and two spars were precured, skin and corrogated subsurface were cocured together while attaching the substructure.
Metal: Skin is an extrusion .25 inches thick with four ribs and two spars that are constructed using rivets and riveted onto the skin.

Part 2: curved fuselage section 96 X 36

Composite: 36 ply skin with 24 ply substructure. Four ribs and two spars were precured items. The corrogated substructure was cocured to the skin while the other substucture was being attached.
Metal: Skin is .14 sheet metal and substructure .1 sheet metal assembled using rivets. There are four ribs, two spars and ten stringers used in construction. The stringers were added to compensate for the reduced thickness.

Part 3: tail opening cargo door 108 X 144 X 180

Composite: The skin is 36 ply. The main attach beam (144) is 50 ply. All other substructure (three ribs, 180 beam, 108 beam and corrogated skin) is 24 ply.
Metal: Skin is .2 thick, 15 stringers, four ribs and four beams are each .063 thick. There are two main attach beams (144) riveted together back-to-back.

Part 4: low speed leading edge 120 X 60 area

Composite: Skin is 16 ply and eight stiffening ribs are 20 plies. They are cocured.
Metal: Skin is .1 and eight ribs are .056 thick. They are riveted together.

Part 5: rudder overall dimensions 40 X 18

Composite: Two 24 ply skin and two 24 ply corrogated subsurface cocured together with top 12 inches, bottom 18 inches and height 36 inches. Main 40 inch spar 48 plys and two rib caps 24 plys, cocured together. Two subassemblies cured together for final assembly.
Metal: Extruded .3 spar with five cast ribs covered with two .1 skins. riveted together.

Part 6: aileron 24 X 36

Composite: Two 16 ply Skins cocured to fiberglass honeycomb core. 30 ply spar cocured with two 30 ply rib caps. subassemblies mated by curing together.
Metal: Cast single piece spar with caps mated to metal skins and honeycomb by curing. Curing costs and comb costs were taken from FACET.

Part 7: wingbox 120 X 36 X 12

Composite: Front and trailing spars are precured 36 ply. Four ribs are precured 36 ply. Top and bottom skins assemblies are 36 ply cocured to 36 corrogated subsurface. Ribs, spars and skins are final assembled by curing together.
Metal: Skins are .25, four ribs, two spars and ten stringers are .14. Assembled by riveting.

Part 8: fuel cell structure 48 X 96 X12

Composite: Front and trailing spars are 24 ply precured. Four ribs are 24 ply precured. Top and bottom 24 ply skins are cocured to 24 ply corrogated substructure. Assembly is by curing together.
Metal: Skins are .14, four ribs, two spars and ten stringers are .14. Assembled by riveting, sealant required on each rivet and between parts.

Part 9: aileron, low speed 24 X 36

Composite: Two 16 ply skins cocured with two 16 ply corrogated substructures. 30 ply precured spar mated with two 30 ply rib caps. Could also serve as a high speed, minimum thickness used.
Metal: Two .056 skins are riveted to five .056 stamped ribs which are riveted to a rolled .2 spar.

Part 10: fuselage skin 24 X 60

Composite: Two 36 ply skins cocured with two 24 ply corrogated substructures. Two 24 ply precured spars and four 24 ply precured ribs. Assembled by curing.
Metal: Skin .2 riveted to four .063 ribs and two .063 spars. No stiffeners are used.

Simple Parts

Part 11: panel 36 X 48

Composite: 24 ply skin with 16 ply border cocured as a single piece.
Metal: Skin .063, riveted to .063 stiffening frame shaped like an "X" in a box.

Part 12: spar 48 X 3 X 3

Composite: Two "C" shaped 16 ply pieces cocured back-to-back.
Metal: Four .063 "L" shaped pieces riveted to a single .1 piece of webbing to form and "I" shaped spar.

Part 13: curved rib 48 X 4

Composite: 14 plies cured in a curved "C" shape.
Metal: .063 sheet metal brake/roll formed.

Part 14: straight rib 48 X 4

Composite: 14 plies cured in a straight "C" shape.
Metal: .063 sheet metal brake form process.

Part 15: panel 24 X 36

Composite: 24 ply skin with 16 ply stiffening border cured as one piece.
Metal: .063 skin farnham rolled and heat treated riveted to a rubber press formed corrogated stiffening .063 skin.

Part 16: panel 24 X 36

Composite: Manual lay-up used: 24 ply single piece panel cured.
Metal: .14 skin formed by Farnham roll, heat treated.

Part 17: panel 24 X 36

Composite: Manual lay-up: Two 24 ply skins cocured to a fiberglass honeycomb center.
Metal: Two .14 skins cured to an aluminum honeycomb.

Part 18: fairing 24 X 12

Composite: 28 ply form cured as a single piece extra plies for durability.
Metal: .1 sheet metal formed by drop hammer

Part 19: fairing 36 X 120

Composite: 36 ply form cured as a single piece, extra plies for durability.
Metal: Two separate half-size .2 sheet metal pieces stretch formed.

Part 20: curved skin 60 X 24

Composite: 24 ply cure
Metal: .14 skin shaped by strech form.

Part 21: spar 120 X 6 X 6

Composite: Two "C" shaped 12 ply pieces cocured back-to-back with two flat 12 ply caps to form an "I" beam.
Metal: Four .063 "L" shaped pieces riveted to a single .1 piece of webbing to form an "I" beam.

Part 22: curved hat shaped stringer 4 X 120

Composite: 16 plies cured in a form.
Metal: Heat treated .063 sheet metal brake/roll formed.

Part 23: curved hat shaped stringer 4 X 48

Composite: 16 plies cured in a form.
Metal: Heat treated .063 sheet metal brake/rcil formed.

Part 24: straight hat shaped stringer 4 X 120

Composite: 12 plies cured in a form.
Metal: .063 sheet metal brake press formed.

Part 25: straight hat shaped stringer 4 X 48

Composite: 12 plies cured in a form.
Metal: .063 sheet metal brake press formed.

Part 26: straight rib 4 X 48

Composite: 8 plies cured in "C" shape; for low stress only.
Metal: .056 sheet metal brake press formed.

Part 27: straight "L" shaped stiffener 4 X 120

Composite: 16 plies cured in a form.
Metal: Heat treated .063 sheet metal brake press formed.

Part 28: straight "L" shaped stiffener 4 X 48

Composite: 16 plies cured in a form.
Metal: Heat treated .063 sheet metal brake press formed.

Part 29: curved "L" shaped stiffener 4 X 120

Composite: 12 plies cured in a form.
Metal: .063 sheet metal brake/roll formed.

Part 30: curved "L" shaped stiffener 4 X 48

Composite: 12 plies cured in a form.
Metal: .063 sheet metal brake/roll formed.

When a spar is shown with three dimensions, they are the actual dimensions. When a rib is shown, it is the dimensions of the part as if it were rolled flat. For the other three dimensional parts, the wingbox and the fuel tank the height dimension are given as if the the spars and ribs were rolled flat. The actual height for a listed 12 inch dimension would be 8 inches. The actual height of all of the parts that do not have height listed is 2 inches, or 4 inches rolled flat.

NONRECURRING TOOLING MANHOUR COST INDEX

COMPLEX PARTS NO.	COMPOSITE	ALUMINUM	SIMPLE PARTS NO.	COMPOSITE	ALUMINUM
1)	82.08	111.60	11)	19.08	64.80
2)	82.08	118.80	12)	17.28	38.70
3)	158.58	133.20	13)	19.08	4.05
4)	38.52	57.75	14)	19.08	2.25
5)	97.56	258.30	15)	22.68	58.50
6)	75.24	71.10	16)	2.88	15.30
7)	82.08	83.25	17)	10.26	41.40
8)	82.08	83.25	18)	22.68	23.40
9)	82.08	56.70	19)	19.08	57.60
10)	82.08	90.79	20)	19.08	5.85
Total	862.38	1064.74	21)	37.80	50.67
			22)	20.52	7.65
			23)	20.52	6.30
			24)	19.08	4.14
			25)	19.08	3.60
			26)	19.08	4.05
			27)	19.08	2.70
			28)	19.08	2.25
			29)	19.08	3.15
			30)	19.08	2.70
			Total	383.50	399.06

SIMPLE INDEX NUMBERS

COMPLEX PART	SIMPLE PART
.810	.961

DEFAULT VALUES

PERCENT COMPOSITE	PERCENT COMPLEX	INDEX VALUE	DAPCA III ADJUSTMENT
10	10	0.946	0.995
15	20	0.931	0.990
20	30	0.916	0.983
25	40	0.901	0.975
30	50	0.886	0.967
35	60	0.870	0.955
40	70	0.855	0.942

Table 4

RECURRING MANUFACTURING MANHOURS INDEX

COMPLEX PARTS			SIMPLE PARTS		
NO.	COMPOSITE	ALUMINUM	NO.	COMPOSITE	ALUMINUM
1)	224.18	315.53	11)	34.18	123.03
2)	224.18	449.78	12)	29.72	81.30
3)	337.35	785.63	13)	16.68	5.25
4)	132.84	170.10	14)	16.68	3.38
5)	236.28	459.68	15)	43.30	116.48
6)	136.86	457.88	16)	59.22	12.67
7)	539.93	1000.88	17)	151.48	64.22
8)	239.58	1308.82	18)	25.30	9.79
9)	140.24	188.10	19)	82.95	50.63
10)	201.35	213.45	20)	29.47	15.27
Total	2412.79	5349.85	21)	84.11	211.80
			22)	18.11	25.50
			23)	14.81	11.85
			24)	22.61	12.30
			25)	18.19	5.03
			26)	15.78	5.25
			27)	24.49	11.85
			28)	22.09	5.25
			29)	20.47	11.85
			30)	18.06	5.10
			Total	747.70	787.80

SIMPLE INDEX NUMBERS		DEFAULT VALUES			
COMPLEX PART	SIMPLE PART	PERCENT COMPOSITE	PERCENT COMPLEX	INDEX VALUE	DPACA III ADJUSTMENT
0.451	0.949	10	10	0.899	0.990
		15	20	0.849	0.977
		20	30	0.800	0.960
		25	40	0.750	0.937
		30	50	0.700	0.910
		35	60	0.650	0.878
		40	70	0.600	0.840

Table 5

MATERIAL DOLLAR COST INDEX

COMPLEX PARTS

NO.	COMPOSITE	ALUMINUM
1)	2496.00	3374.38
2)	2496.00	743.78
3)	6212.40	1808.01
4)	1229.40	839.00
5)	704.40	232.02
6)	366.30	79.34
7)	10857.00	2640.00
8)	7362.00	1965.10
9)	525.00	141.83
10)	1228.80	339.26
Total	33477.30	12162.72

SIMPLE PARTS

NO.	COMPOSITE	ALUMINUM
11)	454.20	208.39
12)	213.00	124.03
13)	31.20	11.58
14)	31.20	11.58
15)	340.80	104.17
16)	239.62	26.06
17)	479.40	80.39
18)	93.00	41.34
19)	1796.10	413.42
20)	399.00	86.80
21)	477.90	295.60
22)	88.80	28.95
23)	35.70	11.58
24)	66.30	28.95
25)	21.15	11.58
26)	17.70	10.29
27)	132.00	28.95
28)	52.80	11.58
29)	66.00	28.95
30)	26.70	11.58
Total	5062.47	1575.77

SIMPLE INDEX NUMBERS

COMPLEX PART	SIMPLE PART
2.752	3.213

DEFAULT VALUES

PERCENT COMPOSITE	PERCENT COMPLEX	INDEX VALUE	DARCA III ADJUSTMENT
10	10	3.167	1.217
15	20	3.121	1.318
20	30	3.075	1.415
25	40	3.029	1.507
30	50	2.983	1.595
35	60	2.936	1.678
40	70	2.890	1.756

Table 6

NONRECURRING TOOLING MANHOUR COST SENSITIVITY TESTS

COMPLEX PARTS

	RANK TEST		RATIO TEST	
ORDER	DIFF.	PART	PART	RATIO
1	-25.38	9	9	1.448
2	-25.38	3	3	1.191
3	-4.14	6	6	1.058
4	1.17	7	7	0.986
4	1.17	8	8	0.986
6	8.71	10	10	0.904
7	19.23	4	1	0.735
8	29.52	1	2	0.691
9	36.72	2	4	0.667
10	160.74	5	5	0.378

COMPLEX PARTS RANGE

COMPOSITE ALUMINUM INDEX

Totals less high ratio
546.48 / 803.74 = 0.680

Totals less low ratio
644.22 / 629.89 = 1.020

Totals less high rank
546.48 / 803.74 = 0.680

Totals less low range
600.66 ? 576.04 = 1.04

SIMPLE PARTS

	RANK TEST		RATIO TEST	
ORDER	DIFF.	PART	PART	RATIO
11	-16.83	14	14	8.480
11	-16.83	28	28	8.480
13	-16.38	27	27	7.067
13	-16.38	30	30	7.067
15	-15.93	29	29	6.057
16	-15.48	25	25	5.300
17	-15.03	26	26	4.711
17	-15.03	13	13	4.711
19	-14.94	24	24	4.601
20	-14.22	23	20	3.262
21	-13.50	20	23	3.257
22	-12.87	22	22	2.702
23	0.72	18	18	0.969
24	12.42	16	21	0.740
25	12.87	21	12	0.447
26	21.42	12	15	0.388
27	31.14	17	19	0.331
28	35.82	15	11	0.294
29	38.52	19	17	0.248
30	45.72	11	16	0.188

COMPLEX PARTS RANGE

COMPOSITE ALUMINUM INDEX

Total less high ratios
307.18 / 389.16 = 0.789

Total less low ratios
319.78 / 176.76 = 1.809

Total less high rank
307.18 / 389.16 = 0.789

Total less low rank
312.48 / 176.68 = 1.769

Table 7

RECURRING MANUFACTURING MANHOURS SENSITIVITY TESTS

COMPLEX PARTS

RANK ORDER	TEST DIFF.	TEST PART	RATIO TEST PART	RATIO TEST RATIO
1	12.10	10	10	0.943
2	37.36	4	4	0.781
3	47.86	9	9	0.746
4	91.35	1	1	0.710
5	223.40	5	7	0.539
6	225.60	2	5	0.514
7	321.02	6	2	0.498
8	448.29	3	3	0.429
9	460.95	7	6	0.299
10	1069.24	8	8	0.183

COMPLEX PARTS RANGE

COMPOSITE ALUMINUM INDEX

Total less high ratio
1938.36 / 4778.20= 0.406

Total less low ratio
1699.00 / 2797.52= 0.607

Total less high rank
1938.36 / 4778.20= 0.406

Total less low rank
1295.93 / 2254.53= 0.575

SIMPLE PARTS

RANK ORDER	TEST DIFF.	TEST PART	RATIO TEST PART	RATIO
11	-87.26	17	14	4.930
12	-46.55	16	16	4.674
13	-32.32	19	28	4.208
14	-16.84	28	25	3.616
15	-15.51	18	30	3.540
16	-14.20	20	13	3.180
17	-13.30	14	26	3.006
18	-13.16	25	18	2.584
19	-12.90	30	17	2.358
20	-12.64	27	27	2.067
21	-11.43	13	20	1.930
22	-10.53	26	24	1.838
23	-10.31	24	29	1.727
24	- 8.62	29	19	1.638
25	- 2.96	23	23	1.250
26	7.39	22	22	0.710
27	51.58	12	21	0.397
28	73.18	15	15	0.372
29	88.85	11	12	0.366
30	127.69	21	11	0.279

SIMPLE PARTS RANGE

COMPOSITE ALUMINUM INDEX

Total less high ratio
631.52 / 767.01 = .823

Total less low ratio
556.39 / 255.19 = 2.180

Total less high rank
431.96 / 660.20 = 0.654

Total less low rank
556.39 / 255.19 = 2.180

Table 8

MATERIAL DOLLAR COST SENSITIVITY TESTS

COMPLEX PARTS

RANK TEST RATIO TEST

ORDER	DIFF.	PART	PART	RATIO
1	878.39	1	1	0.740
2	-286.96	6	4	1.465
3	-383.17	9	5	3.036
4	-390.41	4	3	3.436
5	-472.38	5	2	3.556
6	-889.51	10	10	3.622
7	-1752.27	2	9	3.702
8	-4404.39	3	8	3.746
9	-5396.90	8	7	4.113
10	-8217.00	7	6	4.617

COMPLES PARTS RANGE

COMPOSITE ALUMINUM INDEX

Total less high ratio
14982.11/ 7478.20= 1.941

Total less low ratio
29047.50/ 7717.32= 3.764

Total less high rank
9081.90/ 5749.61= 1.343

Total less low rank
30090.00/ 8567.17= 3.512

SIMPLE PARTS

RANK TEST RATIO TEST

ORDER	DIFF.	PART	PART	RATIO
11	7.41	26	21	1.617
12	9.57	25	12	1.717
13	15.12	30	26	1.720
14	19.62	13	25	1.826
14	19.62	14	11	2.180
16	24.12	23	18	2.250
17	37.05	29	29	2.280
18	37.35	24	24	2.290
19	41.22	28	30	2.306
20	51.66	18	13	2.694
21	59.85	22	14	2.694
22	88.91	12	22	3.067
23	103.05	27	23	3.083
24	182.30	21	15	3.272
25	213.56	16	19	4.344
26	236.63	15	27	4.560
27	245.81	11	28	4.560
28	312.20	20	20	4.597
29	399.01	17	17	5.963
30	1382.68	19	16	9.195

SIMPLE PARTS RANGE

COMPOSITE ALUMINUM INDEX

Total less high ratio
3812.45/ 1353.57= 2.816

Total less low ratio
4332.72/ 1134.27= 3.830

Total less high rank
1933.77 / 786.77= 2.458

Total less low rank
4946.72/ 1530.74= 3.244

Table 9

Data Analysis

The DAPCA III values for the default parts mix (Tables 4,5,6) have been determined and can be compared to the MLCCM expert estimates for graphite/epoxy adjustment factors shown in Table 1. The data can be evaluated to determine if the indices that are presented change significantly with changes in the data. The data can be evaluated by examining the sensitivity tests performed on the indices. The ratio test eliminates the parts with the least and greatest relative difference between composite and aluminum construction methods and examines the impact when the parts are omitted from the indices. The rank test eliminates the most influential parts and least influential parts by measuring the absolute difference between the composite and aluminum construction methods and examines the impact on the indices. The two tests will provide a range over which the index can vary if significant parts are omitted. The range will be determined by first deleting the three complex part observations and four simple part observations that are identified by each test as significantly high then computing index values with the remaining observations. The process is then reaccomplished, but with the three complex and four simple observations identified by the tests as significantly low. Each index will be examined separately.

Nonrecurring Tooling Manhour Cost Analysis (Tables 4

and 2). The nonrecurring tooling manhour cost index (Table 4) deviates significantly from the expert estimates used in the MLCCM modifying index shown in Table 1. There are several possible explanations. First, while the definitions for tooling cost in FACET and ICAM have the same broad meaning, one-time preparation of the tools prior to each production, they contain different work elements. In FACET, preparing the bagging, building the jigs and loading and preparing the automatic machines represents the tooling cost; there is very little "hard tooling" such as dies and press forms. In the ICAM manual tooling costs include checking machine alignment, making any necessary "hard tooling" dies and blanks as well as jigs for assembly. FACET uses a simpler jig for composite part assembly because access to every area of the part is not required as it would be for riveting, and the part is lighter. This assembly impact can best be seen by comparing the relative tooling costs of parts 24 through 30 to the rest of the simple index (Table 4) where some assembly is required. Second, the tooling costs in the ICAM manual are for 200 units not the first one. The nonrecurring tooling cost data charts all provide the tooling costs to make a total of 200 units. The ICAM manual assumed that tooling costs were a function of the number of units produced. It determined the cost of one unit by dividing the nonrecurring tooling cost chart value by 200 (12:p.4.1-10). The FACET manual computed tooling

cost allocated to the first unit directly (14). Finally, sensitivity analysis (Table 7) showed that several data points impact the data significantly.

The ratio test showed that the aluminum rudder (part 5), which had the lowest ratio, absorbed very high tooling costs in the form of set up charges for the five forgings since each was a different size and the extruded spar. Additionally, the cost was estimated by adjusting a dollar figure. The rudder (part 5) has a significant impact on the aluminum portion of the complex index. It represents almost a quarter or the total manhours. Eliminating that one part would raise the index value to 0.948, which is a greater change than the 0.680 value that is obtained when the three highest ratios are omitted from the index (Table 7). The high cost of the process also made the rudder (part 5) the lowest ranked part. The riveting in the fuselage section (part 2) and the simplicity of the composite leading edge (part 4) are the cause of those being significant in the ratio test. The fuselage section (part 2) remained significant in the rank test because of its complexity and size, the leading edge was almost significant (ranked 7) but was replaced by the fuselage section (part 1) which was more complex. The two tests of the simple parts index yielded nearly identical results. The panel (part 11), constructed using an X-frame back support, and the panel (part 15), constructed with a beaded aluminum back, are high because

they have a process, rubber press, which requires extensive tooling in addition to riveting. The long fairing (part 19) was significant on both tests because the aluminum process required two distinct molds to make the equivalent part. The small manual lay-up panel (part 16) was significant because the tooling required for manual lay-up is almost nil. It was not selected by the rank test because it was a very simple part. Instead, the rank test selected part 12 which had two composite pieces and five aluminum ones. The ten foot spar (part 21) that was constructed by cocuring two composite pieces versus five aluminum pieces riveted together was the next choice for both tests.

The tooling costs shown in the index (Table 4) were most effected by complexity of the parts. The more assembly required, the more likely that the parts would be significantly different because of riveting. The tooling cost for riveting is very high because it involves drilling holes, aligning holes and holding them in alignment while a rivet is installed. This is reflected in the relative stability of the complex parts index compared to the simple index. The extreme variance in the simple index is a result of eliminating four of the parts that required some assembly as well as four very efficient metal processes. Using an index with only the high range values selected would still leave the index value below the MLCCM adjustment factor estimated by the experts shown in Table 1. The elimination

of rivets in the composite part assembly process is the primary cause for the discrepancy. For example, riveting nonrecurring tooling manhour costs for the wingbox (part 7) are 63 additional hours, which if added to the composite process would change the index for that one part from 0.989 to 1.74, very close to the MLCCM number of 1.73. The decision for not including riveting in the composite assemblies is based on the fact that FACET does not allow for it. There may be some cases where riveting is desired to ensure any delamination does not have a catastrophic effect in flight. Failure to include some riveting is a limitation of FACET that could be adjusted with the ICAM manual if riveting was planned.

Recurring Manufacturing Manhours Analysis (Tables 5 and 8). The recurring manufacturing manhours index (Table 5) is significantly effected by the number of rivet used. The rivet spacing selected was a rivet each 0.625 inches as shown in the ICAM manual (12:p.4.2-13). To lessen the impact of riveting, 80 percent automatic riveting was chosen for all processes. Had manual riveting been selected, rivet assembly manhours would have increased 190 percent (12:p.4.2-24). The logic behind using 80 percent automation is first, many firms are beginning to use automated riveting machines, and second, it provided some compensation for the composites using no rivets at all. Riveting was also considered when selecting parts. The wingbox (7) and the

fuel cell (8) address the problem of blind riveting. The fuel cell also addresses the problem of sealant for rivets and between surfaces which increases riveting manhours by an average of 50 percent (12:p.4.2-24). If the fuel cell was eliminated, the complex part index value would change from 0.451 to 0.538.

Sensitivity tests (Table 8) confirmed the significance of riveting assembly and parts complexity. Both tests selected the same the fuel tank as the most significant. The sealant required on the rivets and the pieces required extra manhours in the aluminum process which were not needed in the composite process because of the epoxy. Both tests selected the cargo door as significant because of the amount of riveting required. The rank test selected the wing box (part 7) because it was such a large, complex part that any relative difference made a significant absolute difference. The relative difference would have made it the next part selected by the ratio test. The ratio test selected the high speed aileron (part 6) because of the relative difference caused by the casting charges. The impact of complexity was confirmed by both tests as they selected the same parts (4,9,and 10) which are generally less complicated than the other complex parts. Part 4 is the low speed leading edge which requires comparatively little riveting. Part 9 is the low speed aileron which reqires a large number of plies in the composite spar, but very little riveting in

the aluminum aileron. Part 10 is the section of fuselage that uses a very thick skin and no stringers. The simple parts index was influenced by many of the same parts that influenced the nonrecurring tooling manhour cost index (Table 4). The cocured spars (parts 12 and 21) both have significantly fewer manhours than their aluminum counterparts and are large parts. Consequently, both tests selected them. Both tests selected the panel with the X frame support construction (part 11) and the panel with the beaded support construction because of the significant riveting costs and the use of the rubber press. The rank test selected the two panels (parts 16 and 17) that were constructed using manual lay-up. The manual lay-up process took many more manhours than the aluminum process even when riveting was considered in part 17. The ratio test would have selected part 17 as its next choice. For the simple parts that did not require any assembly, the number of composite plies was a significant cost factor for the composite parts while length was significant for the metal parts. Length was significant because the ICAM manual assumed any part over six feet long required two people to work on it (12:p.4.1-43). Both tests selected a ten foot spar (part 28) that caused a high ratio because it used enough plies that it was significantly more time-consuming even though it was ten feet long. The ratio test selected a straight hat shaped stringer (part 25) because the ply

lay-up was more time consuming than the brake press bending. The rank test selected the thick ply ten foot fairing because of number of manhours spent building it was large even though the relative significance of the difference was not.

The wide range of values shown by shaping the simple parts is logical. The simple parts index lost four large assembly parts in both tests. The four parts requiring assembly were much larger than the average part. The rank test further emphasized the point by eliminating the few large pieces that were adversely effected by the number of plies. The absence of rivets clearly shows the advantages of composite assembly methods. If rivets were added to the complex composite part assembly process, each part would show an average increase of 5 standard hours for a total of 900 actual hours. An increase in 900 hours for composites would change the complex index number value (Table 5) from 0.451 to 0.619. The DAPCA III adjustment would increase a maximum an additional 12 percent at 40 percent composite material. Still, the manufacturing manhours index shows a tremedous advantage for composite material. The material dollar cost index is much less generous showing dollar costs of 2.7 to 3.2 times higher than the comparable aluminum part.

<u>Material Dollar Cost Analysis (Tables 6 and 9)</u>. The material dollar cost is not effected by riveting or part

complexity. The amount of material in most parts is based on the equations used to generate the number of plies to metal thickness which assume a weight savings of 15 percent (18). Accordingly, there is relatively little change in the index value from complex parts to simple parts. However, some cases of excess plies existed because they were needed for durability. The largest variance in plies is in the simple parts. The panels and skins, parts 15,18,19, and 20 in particular, had thicker surfaces than the metal to withstand impacts that metal can absorb easily. Additionally, some stringers and ribs had extra plies to compensate for heat-treated metal that was extra stiff. These planned variances in the number of plies can explain the difference between the complex and simple index values in Table 6.

The sensitivity tests explain a few of the other variances in the data. Both tests identified the large wing box (part 7) and fuel cell (part 8) as significant. These large parts weigh so much that when the pounds are multiplied be the dollar costs, the cost becomes significantly high. The actual weights are nearly equal with the composite parts being one percent higher. This indicates that the parts may have been thicker than needed or that the corrogated support was not required. The ratio of composite part weight to metal part weight can be determined by dividing the total costs in Table 6 by the

dollar cost of each material and then multiplying by the scrap rate. The weight ratio for complex parts is 70 percent and the simple parts ratio 82 percent. The composite to aluminum weight ratio for the complex parts without the extruded fuselage section (part 1) is 89 percent. The huge block of material that was used to create the skin is representative of the type of waste that accompanies milling operations. Normal extrusions are more efficient than sheet metal operations while milling operations are much less (7:A.41). The lack of machining operations in the ICAM manual made the extrusion the most representative of the metal extraction methods of production for manhours, but the large block was all counted in the material index. A final observation about the material dollar cost index is that any part with a large quantity of composite material is going to have a very large cost. Had a different dollars/pound ratio been used, the variance would have been even greater. For example, at 35 dollars a pound, the complex index changes from 2.752 to 3.21 and the simple index jumps from 3.213 to 3.748. Thus, the material dollar index is very sensitive to material price and the number of plies used in construction. Both cause and effect relationships are obvious and logical. A summary of all of the analysis will condense the findings.

Analysis Summary

The analysis of the data revealed numerous differences between processes used to produce parts. The potential

sources of bias were considered and explained. The two major sources were processes or considerations that affected the relationships of all the parts and specific parts that were constructed in such a manner as to influence indices significantly. Some individual parts did have a notable impact on specific indexes, but the impact can be explained.

There was very little bias induced by any individual part into all three indices. Only three observations, parts 4, 6, and 16 appear as outliers in all three sensitivity tests; however, none of them have the same impact on every index. Part 4, the low speed leading edge, raises the nonrecurring tooling manhour index and the recurring manufacturing manhours index as an outlying high value, but is a low value in the material dollar cost. This can be explained by the simplicity of both the metal and the composite design which makes it track like a simple part. Additionally, it has fewer plies than any other complex part. Increasing the number of plies would leave it as an increasing influence on the nonrecurring tooling manhours and recurring manufacturing manhour indices, but eliminate it from the material index until it was over 104 plies when it would appear as a high cost variance part. Part 6, the aileron with a honeycomb center appears in all three indices because of the cast spar used in the aluminum process. The nonrecurring tooling cost are very similar because they include many of the same elements. The FACET costs for

assembly were used for bonding both parts so there are no riveting costs in the metal version. The casting caused the part to be a high value manufacturing manhour influence, while making it a low value material cost item when compared to a 30 ply composite spar. Part 16, the manual lay-up panel, also had logical explanations for its continued appearance. It was a low nonrecurring tooling manhour influence because the other processes had tooling and it did not. It was a high recurring manufacturing manhour influence for the same reason. It appeared as a high value material dollar cost deviation because, as a panel, it required an excess number of plies for durability. Thus, the three possible candidates for influencing all of the indices have logical explanations for their behavior. The next source of broad data bias that should be examined are processes which are cost drivers.

The two most likely influences to the indices are the lack of riveting for the composite parts and the number of plies used in construction. These two problems must be addressed by engineers to be more accurately assessed. Both issues revolve around the relative strengths and durability of the two materials. The issue of using rivets in construction must be settled by an engineer. The projects examined in the DOD/NASA Structural Composites Fabrication Guide use rivets only when binding composites to metals or when attaching fixtures (17:vol.1,pp.9.1-9.43). Both of

those operations were eliminated from the parts considered in developing the indices.

The second major source of bias is the number of plies that are used in construction. The number of plies directly affects the manufacturing manhours and the material dollar cost. To gain complete confidence in all of the parts used in this index, an engineer should evaluate them for their structural comparability. The ply to metal thickness ratios were based on material strength and a theoretical weight savings (18). Additionally, when there was a possible question of strength and durability, extra plies were added. Close engineering evaluation may reveal some differences that would effect the position of composite materials in the two indices.

The optimum solution to the problem of determining the impact of riveting and the number of plies on the index values would be to contract for actual composite material cost data and replicate the process. The same procedures that were used in developing the ICAM manual could be used. An independent analytic corporation could receive proprietary cost data that could be examined with the confidence that neither the government nor other contractors would have access to it. That corporation could then compare actual costs of a select group of items that have been specifically tracked by industrial engineers through the production process. Until such a project is undertaken,

the suboptimal solution would be to have the parts examined by FACET and the ICAM manual be designed by engineers. Before that is done, the question of what tooling costs are being captured by the two models must be answered.

The documentation for the FACET computer model is extremely limited, though answers about use can be obtained by calling the contractor (14). In using FACET, the one question that was not answered completely was what tooling costs were being captured by the model. The input into the computer to determine tooling cost is the total number to be produced and the rate of production. Both factors have an impact on nonrecurring tooling costs. They also impact recurring tooling cost. Using unit one values limits the possibility that the costs presented are recurring costs because they are still extremely large. If the impact of no riveting is considered the cost provided by FACET would result in index values very similar to the expert opinion values found in the MLCCM adjustment factors for graphite epoxy (5:vol.1,74). The behavior of tooling costs when different composite processes are used would also indicate that the nonrecurring tooling costs are being captured. The manual lay-up, manually cut parts had significantly lower tooling costs than the automated processes while the additional time required to manipulate the material was captured by the recurring manufacturing manhours. Still, though the evidence that FACET does collect nonrecurring

tooling costs is significant, further investigation in the area should be accomplished before the nonrecurring tooling manhour cost index can be used with confidence. Still, even with the remaining questions about documentation and engineering accuracy, some conclusions about the indices can be drawn, the research questions can be answered and recommendations can be made.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Thesis Summary

This thesis sought to answer several research questions to meet the research objective of developing an index of adjustment factors that can be used to modify the DAPCA III parametric airframe cost estimating model. The first set of research questions concerned the usefulness of choosing the Rand DAPCA III model as a basis for modification by adjustment factors instead of any of the other parametric models that are available. The second set of research questions addressed developing the data, validating the data, and then developing and validating the resulting index.

The process of answering the research questions was lengthy. The questions on the DAPCA III model were answered after an extensive review of the cost model literature. The composite material data collection and validation was accomplished using the FACET computer program. The metal parts data collection and validation was accomplished using the ICAM Manufacturing Design Cost/Design Guide. The data was then developed into an index for analysis and verification. Each step of the process presented difficult and unique problems.

Reviewing the literature in any field is an ongoing

process that is never complete. Since the initial review of the literature was completed, progress has been made on updating the MLCCM data base to include bombers to broaden the base of application and the adjustment factors are being redeveloped accordingly. This information is expected to be available around November 1983. Individual corporations are developing their own cost models that are tailored to their corporate cost structure. Boeing, Northrop, Grumman, and Lockheed Aerospace Corporations all have models which they use in estimating cost that are not available for proprietary reasons (12). Given these limitations, the review of the literature was sufficiently complete to adequately evaluate the suitability of DAPCA III as a format for modification. Most of the models found in the literature used either specialized data bases or dollar output that limited their usefulness. The DAPCA III model did not suffer from those limitations and had other additional benefits in that a format for adjusting the output was incorporated into the model and made the one-step modification objective of the thesis plausible. In addition to reviewing the literature on airframe cost models, the thesis evaluated parts cost models to determine the validity of choosing FACET and the ICAM Manufacturing Cost/Design Guide as suitable vehicles for data collection. The only other model found was the predecessor to FACET, ACCEM. The limitations of ACCEM were readily apparent, so FACET was

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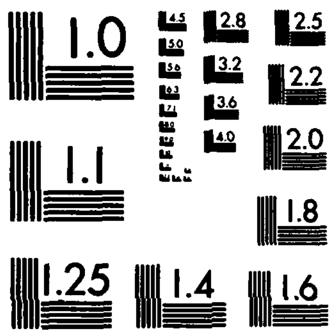

MICROCOPY RESOLUTION TEST CHART
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selected. Finding actual information on the FACET model was difficult. Mr. Reinert provided a copy of the FACET User's Guide which contained the cost estimating relationships and the necessary code to use the program. There was no discussion on how the CERs were developed. The evaluation of FACET in the DOD/NASA Composite Structures Fabrication Guide provides some information that could be used to determine the validity of the FACET output, but little else has been published. A single article published in "Estimator" magazine provided additional information of the validity of the model (9). The ICAM manual was the sole source of information on metal parts. The manual was used as an alternative to capturing actual data on metal parts. The actual cost data on parts is proprietary because of the vast amount of information that could be drawn from it about individual corporate finance and management actions. When the literature review was completed, the two models were used to develop the data.

Data collection did not go smoothly. The Air Force version of FACET could not be made to run on the computers at Wright-Patterson AFB. The Advanced Data Management model in Princeton, New Jersey was used to collect the data. The parts designed were developed by the author using guidelines provided by Mr. Wallace (18) and Mr. Reinert (16). The metal parts were designed using the guidelines provided in the ICAM manual and by evaluating engineering drawings on the

B-52 and the F-111. No engineers ever looked at the final part designs, nor did any of the designs ever come directly from a part actually on an aircraft. The parts were kept very simple in design to facilitate using the two models. No accessories were put on the parts, only the minimum amount of structure was used to capture the essence of each part. For example, none of the panels had hinges or fastening attachments; however, if drilling was required for screw holes, it was accomplished and accounted for. Once the data were collected, they required some adjustment to make them comparable. When the adjustment was completed and explained, the indices were developed. The indices that were developed were sufficiently analyzed to enable conclusions to be drawn as to their validity and usefulness in meeting the thesis objective.

Conclusions

The thesis objective of developing an index of adjustment factors to reflect the differences between composite material and aluminum airframe costs has been achieved, but with some limitations. The research questions posed can be answered, though not all can be answered with extreme confidence. The questions that concern DAPCA III are the easiest to answer, the questions on the validity of the data and the resulting index are the most difficult to answer.

The Rand DAPCA III model is the best choice for

modification, given the airframe cost estimating models that are available. The most outstanding assets of the DAPCA III model were the fact that the figures to be modified were time insensitive, and the input modifications were universal factors. The use of manhours instead of dollars to determine cost was the deciding factor in favor of DAPCA III over the other slightly more accurate J. Watson Noah model. The manhour dollar cost in any year can be determined by simply multiplying the hours by the cost per hour for that year if hours are what is measured. When dollars are used to measure costs, they must be adjusted from year to year for inflation, and from corporation to corporation for accounting practices. Both approaches have limitations on their accuracy. The manhour approach requires that all of the collateral costs of manufacturing such as overhead be incorporated into the dollar figure used to multiply the manhours collected. The dollar approach requires accuracy in adjusting for inflation and often requires extensive research into corporate financial practices. The commonality of manhours was the other outstanding asset of the DAPCA III approach. Each corporation tracks manufacturing manhours for the government. Costs are justified and charged to the government on the basis of hours work expended. Therefore any index ratio derived from manhours would be a logical means of modifying those costs. Examination of the Rand data base also contributed to the

selection.

The second research question concerned the validity of the Rand Corporation data base. The absolute validity could not be determined in the scope of this paper as the question has not been completely answered in the nearly 30 years that the data base has existed and undergone modification. However, the validity of the data base coampared to the other data bases available relative to this thesis was established. The Rand corporation data base had the widest variety of aircraft types and the most current sample of aircraft. The PRC data base contained aircraft from as far back as 1945 in it with the latest one being produced in the late 1950s. The 25 year old data did reasonably well in predicting the cost of early 1960s aircraft, but has not been used to estimate the cost of any newer aircraft. The J. Watson Noah model used the Rand data base, with some modifications, to develop CERs. The MLCCM data base was as accurate as the Rand data base, but it did not have the wide range of applicability that the Rand data did because it only included fighters and cargo aircraft. When modification of the MLCCM model is complete, the two data bases should be compared again. Having fully answered the research questions concerning the DAPCA III model it is possible to address the research questions on data collection and index development.

The choice of how to format the index was a function of

the model selected. Once the DAPCA III model was selected, the modification factors available in it were the logical choice for a modification format. The use of comparison between metal and composite parts instead of using expert opinion was an arbitrary choice made to explore new avenues to the problem. The use of two cost models to collect the costs was the only means of collecting costs in the DAPCA III format. If actual aluminum cost had been used, they would have been determined by applying an industry wrap rated to the government's cost of the part to divide the cost into the three elements used in the index. The FACET model would still have been used. Given the format of the index and the availability of data sources, the answers to how the data should be collected and used were readily apparent and fully explained in the methodology. The question concerning the validity of the data and therefore the validity of the index was much more difficult.

The validity of the data collected has been the most difficult question to answer. The data validity was effected by two main factors: 1) realism and comparability of the parts and 2) comparability and accuracy of the costs generated by the models. The total reliance on engineering studies and comparisons of the two estimating models to validate the resulting data is a major limitation to the thesis effort. While the parts were constructed using a sound approach and are reasonable and relatively free of

bias, they could have been improved upon. The parts that were input to the two models should have been designed by engineers fully qualified to recognize and compensate for the nuances of stress, elasticity, and aerodynamic forces. Using engineers to design the parts would have provided increased face validity to the thesis effort if nothing else. Still, considering the long range cost objectives of a DAPCA III estimate, the comparability and realism of the data is satisfactory.

The second impact on the data is the comparability and accuracy of the costs developed by the two models. The accuracy of the costs collected by the FACET model has been tested with excellent results (9:9). The ICAM manual is an average of the actual costs of the industry and as such, produces an average cost that can be adjusted for each corporation. Since the DAPCA III model estimate is used long before any production source has been selected, an industry average is an ideal approach. For these reasons, the accuracy of the costs provided by the two models is satisfactory for developing the thesis index. The remaining question is the comparability of the output of the two models. There is no problem with material dollar cost comparability because the costs for the metal parts were determined independently of the ICAM manual in a manner that made them compatable. The dimensions of the metal parts were converted to cubic inches which was converted to

pounds. FACET provided the output in pound of material required. The actual material in the parts was then multiplied by an industry average scrap rate to determine the total material used. Again, because of the long range nature of the DAPCA III estimate, no other process could provide more accurate or comparable information. There is no problem with the recurring manufacturing manhours used in each part. Both models incorporate the same costs. The costs documented in the ICAM Manufacturing Cost/Design Guide can readily be traced in the output from a FACET computer run and in the FACET CERs that are provided. There is a potential problem with the comparability of the nonrecurring tooling cost information. The two models use slightly different terminology in discussing tooling costs in general. There is a possibility that the costs captured are not identical. The objective of the index has been to capture the one-time tooling production costs associated with producing a product, not the costs producing each product. Each separate lot has been considered a production run. The production tooling cost in the ICAM manual were for the 200th unit and represented an industry average. The FACET costs were developed by setting a production rate and a number to be produced. The rate selected was ten items per shipset and ten shipsets a month. To compensate for the fact that the ICAM manual has no specified rate, the first unit cost was selected. Mr. Paner indicated that choosing

the first unit cost would negate the impact of lot size and quantity. Until the two values can be more accurately defined, some doubt will remain about the data used to develop the nonrecurring tooling cost index. The final research questions concerned the validity and sensitivity of the indices developed.

The validity of the indices is directly dependent on the data used to construct them. The conclusions reached about the input data support a conclusion of validity for the recurring manufacturing manhour index and the material dollar cost index. The validity of the nonrecurring tooling cost index cannot be determined at this time. The sensitivity of the indices was evaluated thoroughly. In general, the consistent treatment of assembly costs in the complex part index, compared to the simple index treatment, gave the complex parts index greater stability in the nonrecurring tooling hanhour cost index and the recurring manufacturing manhour index than the simple index. The wide variation in number of plies from a low of 16 to a high of 50 in the complex parts had a significant impact on the variation of the index. The conclusion reached in answering the question of index sensitivity is that they are sensitive. The two factors which most effect the indices are the number of plies and the assembly method. Using engineers to design the parts would allow greater confidence in the parts index and may reduce the sensitivity by

narrowing the range of assembly methods and variation in the number of plies. Having answered all the research questions, a summary conclusion can be reached about the research objective.

Conclusion Summary

The recurring manufacturing hours index and the material dollar cost index that have been developed can successfully reflect enough of the differences between composite material and aluminum to be useful in modifying the DAPCA III parametric model. The rough method of developing the parts used to collect the data reduces the confidence that the true relationship between composite material is perfectly reflected. Uncertainties in the exact relationship between the tooling cost captured in FACET and the tooling costs captured in the ICAM manual must be resolved before the index can be used.

Recommendations

The first recommendation is that further documentation for the FACET model should be developed to provide clear operating instructions and a thorough explanation of the costs that are being captured. Expertise in operating the FACET model was gained only through a great deal of trial and many errors. FACET could be significantly improved if the program were easier to operate. Much of the data that the input program asks for are not used in the actual CERs. Shape has no effect on the cost of a part, yet shape is

required. If shape does have an effect on cost then it should be included and should be requested for all substructure as well as the assembly. The ability to edit the data more readily and an automatic crosscheck for feasibility would also help the program run. In general, once the idiosyncracies of the program were mastered, FACET was very useful.

The second recommendation is that this study should be replicated with a larger number of parts that have been designed by an engineer. The sample size could be larger and incorporate a wider variety of metal parts. All of the most common metal processes were used, but a wider sample of each type would help eliminate any bias. Larger samples of some parts were not included for that reason. The need to use dollars to compute manhours required for casting, forging and extrusion made those estimates less reliable than the sheet metal ones so they were limited. Should the ICAM manual ever be modified to measure manhours for those processes, or actual manhour costs for some forged, cast or extruded parts used, more of those type parts should be included. The recommendation to have the parts designed by an engineer adds face validity to the project.

The third recommendation is to examine the other adjustment factors used by the DAPCA III model, flight test, engineering, and nonrecurring material and manufacturing manhour costs, to ensure that there is little difference in

their costs for aluminum and composite material. The models used in this thesis were not able to examine those cost relationships. For the research effort to be complete, they must be examined even if they prove to be insignificant.

If these recommendations are carried out, the resulting index will definitely be a useful long range planning tool.

APPENDICES

APPENDIX A

COMPOSITE MATERIAL PARTS CONSTRUCTION

COMPOSITE MATERIAL PARTS CONSTRUCTION

The FACET inputs required to generate the cost of the composite parts used in the thesis are shown below. Additional inputs are needed to use FACET, but they do not effect the output used in this thesis. Each part is described by showing what processes and dimensions were used. The parts are broken down into subassemblies and assembly processes where applicable. All dimensions needed for the program are provided beneath the process list. All measurements are in inches. The length and width dimensions are for the surface area of the part. Spars are always considered to run parallel to the length and ribs are perpendicular to spars. When a part is used more than once in an assembly, the part is preceded by the number of times it is used. The FACET program automatically applies a realization factor and learning curve for each step selected. The CERs associated with each step and the realization factor used are provided in the User's Guide (18:vol.3,pp.32-83).

FACET has coded 24 different fabrication steps that describe composite part construction. Not all of the steps are required for any single composite part. Many of the steps can be accomplished with different processes. The codes for each step and its associated process options are provided below.

FACET INPUT CODES

Code	Step/process
01	Tool and Material Preparation
02	Material Dispensing 1. manual 2. automated
03	Ply Cutting Operations 1. manual 2. Gerber blade 3. laser 4. waterjet
04	Lay-up and Ply Handling 1. manual 2. robot 3. auto tape layer
05	Peel Ply
06	Debulk 1. hot 2. cold
07	Polyglycol Core Chucking
08	Trim and Cut Core to Template
09	Contour Cutting 1. Apex contour mill 2. gantry and planner mill 3. Wadkins router
10	Step Cutting/Area Step Cutting 1. Apex contour mill 2. gantry and planner mill 3. Wadkins router
11	Cutout Cutting 1. Apex contour mill 2. gantry and planner mill 3. Wadkins router
12	End Mill Cutting 1. Apex contour mill 2. gantry and planner mill 3. Wadkins router
13	Profiling - Marwin NC

14	Honeycomb Core Release and Cleaning
15	Details prefitting for Assembly
16	Detail Preparation
17	Adhesives Application
18	Parts Loading to Assembly Fixture
19	Bagger and Bleeder Ply Application 1. bleeder-disposable 2. bleeder-reusable 3. no bleed-disposable 4. no bleed-reusable
20	Curing 1. autoclave 2. Oven
21	Post Curing
22	Part Removal
23	Finishing 1. drill holes-rout edges 2. drill holes- no rout edges 3. no drill holes-rout edges
24	Wrapping and Packaging

LIST OF COMPLEX PARTS

PART 1: Fuselage skin

codes	skin	corrugation	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	3		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	1	1
20			1	1	1	1
21						
22			x	x	x	x
23						
24						

Dimension Inputs

	Length	width	area	Perimeter	Ply	Bldr/ Dablk	Tape area	Tape prmtr
Skin	96	36	3456	264	36	6	0	0
Corr.	96	36	3456	264	24	6	0	0
2/Spar	96	4	384	200	24	4	0	0
4/Rib	36	4	144	80	24	4	0	0
Assy 1	96	36	3456	264	0	0	0	0
Assy 2	96	36	3456	264	0	0	336	684

PART 2: Fuselage skin

codes	skin	corrogation	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	3		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	1	1
20			1	1	1	1
21						
22			x	x	x	x
23						
24						

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Dbblk	Tape area	Tape prmtr
Skin	96	36	3456	264	36	6	0	0
Corr.	96	36	3456	264	24	4	0	0
2/Spar	96	4	384	200	24	4	0	0
4/Rib	36	4	144	80	24	4	0	0
Assy 1	96	36	3456	264	0	0	0	0
Assy 2	96	36	3456	264	0	0	336	684

PART 3: Cargo door

codes	skin	corrogatiom	beams	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	3		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	1	1
20			1	1	1	1
21						
22			x	x	x	x
23						
24						

Dimension Inputs

	Length	width	area	Peri- meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
Skin(1)	180	108	7776	432	24	3	0	0
Corr.	180	108	7776	432	24	3	0	0
Beam	180	4	720	368	24	3	0	0
Beam	144	4	576	296	50	10	0	0
Beam	108	4	432	224	24	3	0	0
Rib	81	4	324	170	24	3	0	0
Rib	54	4	216	106	24	3	0	0
Rib	27	4	108	62	24	3	0	0
Assy 1	180	108	7776	432	0	0	0	0
Assy 2	180	108	7776	432	0	0	594	1200

(1) Skin and corrogation are triangle shaped; hypoteneuse is given, height is 144

PART 4: Leading edge

codes	skin	Ribs	Assembly 1
01	x	x	
02	2	2	
03	2	2	
04	3	3	
05			
06	2	2	
07			
08			
09			
10			
11			
12			
13			
14			
15			
16			
17			x
18			x
19	4	4	
20	1	1	1
21			
22			x
23			
24			

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
Skin	120	60	7200	360	16	2	0	0
8/Ribs	60	2	120	124	20	2	0	0
Assy 1	96	36	3456	264	0	0	0	0

PART 5: Rudder

codes	skin	corrogatiom	spar	ribs	assy 1	assy 2	assy 3
01	x	x	x	x			
02	2	2	2	2			
03	2	2	2	2			
04	3	3	3	3			
05							
06	2	2	2	2			
07							
08							
09							
10							
11							
12							
13							
14							
15							
16							
07							x
18					x	x	x
19					4	4	4
20					1	4	4
21							
22					x	x	x
23							3
24							

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
2/Skin(1)	36	12/18	540	102	24	4	0	0
2/Corr.	36	12/18	540	102	24	4	0	0
Spar	40	4	160	88	48	8	0	0
Ribcap	12	4	24	28	24	4	0	0
Ribcap	18	4	36	40	24	4	0	0
Assy 1	36	18	540	102	0	0	0	0
Assy 2	40	18	546	115	0	0	0	0
Assy 3	40	18	546	115	0	0	1080	102

PART 6: Aileron

codes	skin	honeycomb	spar	rib	assembly 1
01	x		x	x	
02	2		2	2	
03	2		2	2	
04	3		3	3	
05					
06	1		1	1	
07		x			
08		x			
09					
10					
11					
12					
13		x			
14		x			
15					
16					
17					x
18					x
19	4		4	4	4
20	1		1	1	1
21					
22	x		x	x	x
23					3
24					

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
2/Skin	36	24	864	120	16	2	0	0
Hnycmb(1)	34	22	748	112	2"	0	0	0
Spar	36	4	144	80	30	3	0	0
2/Ribs	24	4	96	56	30	3	0	0
Assy 1	36	24	864	120	0	0	1728	240

(1) honeycomb thickness listed under ply, original size 36 X 24

PART 7: Wingbox

codes	skin	corrugation	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	2		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	4	4
20			1	1	1	1
21						
22			x	x	x	x
23					3	
24						

Dimension Inputs

	Length	width	area	Perimeter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
2/Skin	120	36	4320	312	36	6	0	0
2/Corr.	120	36	4320	312	36	6	0	0
4/Spar	120	12	1440	268	36	6	0	0
4/Rib	36	12	432	96	36	6	0	0
Assy 1	120	36	4320	312	0	0	0	0
Assy 2	120	36	4320	312	0	0	2496	1376

PART 8: Fuel cell

codes	skin	corrogatiom	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	2		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	4	4
20			1	1	1	1
21						
22			x	x	x	x
23					3	
24						

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
2/Skin	96	48	4608	288	24	4	0	0
2/Corr.	96	48	4608	288	24	4	0	0
4/Spar	96	24	2304	240	24	4	0	0
4/Rib	48	24	2304	144	24	4	0	0
Assy 1	96	48	4608	288	0	0	0	0
Assy 2	96	48	4608	288	0	0	576	592

PART 9: Aileron

codes	skin	corrogatiom	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	1	1		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	4	4
20			1	1	1	1
21						
22	x	x	x	x	x	x
23						3
24						

Dimension Inputs

	Length	width	area	Peri- meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
2/Skin	36	24	864	120	16	1	0	0
2/Corr.	36	24	864	120	16	1	0	0
1/Spar	36	4	144	80	20	2	0	0
2/Rib	24	4	96	56	20	2	0	0J
Assy 1								
Assy 2								

PART 10: Fuselage skin

codes	skin	corrugation	spar	rib	assembly 1	assembly 2
01	x	x	x	x		
02	2	2	2	2		
03	2	2	2	2		
04	3	3	3	3		
05						
06	2	2	2	3		
07						
08						
09						
10						
11						
12						
13						
14						
15						
16						
17						x
18					x	x
19			4	4	1	1
20			1	1	1	1
21						
22			x	x	x	x
23					1	
24						

Dimension Inputs

	Length	width	area	Perimeter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
1/Skin	60	24	1440	168	36	6	0	0
1/Corr.	60	24	1440	168	24	4	0	0
2/Spar	60	4	240	128	24	4	0	0
4/Rib	24	4	96	56	24	4	0	0
Assy 1	60	24	1440	168	0	0	0	0
Assy 2	60	25	1440	160	0	0	216	448

SIMPLE PARTS

codes	PART 11 panel	PART 12 spar&assy	PART 13 rib	PART 14 rib	PART 15 panel
01	x	x	x	x	x
02	2	2	2	2	2
03	2	2	2	2	2
04	3	3	3	3	3
05					x
06	2	2	1	1	2
07					
08					
09					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19	4	3	4	4	4
20	1	1	1	1	1
21					
22	1	1	1	1	
923					
24					

Dimension Inputs

	Length	width	area	Peri- meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
Part 11	48	36	1728	168	36	6	0	0
Part 12	48	12	576	120	16	2	0	0
Part 13	48	4	192	104	14	1	0	0
Part 14	48	4	192	104	14	1	0	0

	PART 16	PART 17: panel			PART 18	PART 19	PART 20
codes	panel	skin	comb	assy	fairing	fairing	skin
01	x	x			x	x	x
02	1	1			2	2	2
03	1	1			2	2	2
04	1	1			3	3	3
05							
06	2	2				1	2
07							
08			x				
09			3				
10							
11							
12			3				
13							
14							
15							
16							
17							
18				x			
19	4			3	2	4	4
20	1			1	1	1	1
21							
22	x			x	x	x	x
23				3	1		
24							

Dimension Inputs

	Length	width	area	Perimeter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
PART 16	36	24	864	120	24	3	0	0
17:SKIN	36	24	864	120	24	3	0	0
17:comb(1)	34	22	748	112	1"	0	0	0
17:assy	34	24	864	120	0	0	1728	240
PART 18	24	12	288	72	28	3	0	0
PART 19	120	36	4320	312	36	6	0	0

(1) The thickness of the comb is listed under plies.

codes	PART 21: Spar tops	web	assy	PART 22 stringer	PART 23 stringer	PART 24 stringer	PART 25 stringer
01	x	x		x	x	x	x
02	2	2		2	2	2	2
03	2	2		2	2	2	2
04	3	3		3	3	3	3
05				x	x		
06	2	2				1	1
07							
08							
09							
10							
11							
12							
13							
14							
15							
16							
17							
18			x				
19			4	3	2	4	4
20			1	1	1	1	1
21							
22			x	x	x	x	x
23							
24							

Dimension Inputs

	Length	width	area	Peri-meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
21: top	120	12	1440	264	12	1	0	0
21: web	120	6	720	252	12	1	0	0
21: assy	120	12	1440	264	0	0	0	0
PART 22	120	4	480	248	16	4	0	0
PART 23	48	4	192	104	16	4	0	0
PART 24	120	4	480	248	12	1	0	0
PART 25	48	4	192	248	12	1	0	0

	PART 26	PART 27	PART 28	PART 29	PART 30
codes	rib	stiffener	stiffener	stiffener	stiffener
01	x	x	x	x	x
02	2	2	2	2	2
03	2	2	2	2	2
04	3	3	3	3	3
05					
06	2	2	2	2	2
07					
08					
09					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19	4	4	4	4	4
20	1	1	1	1	1
21					
22	x	x	x	x	x
23					
24					

Dimension Inputs

	Length	width	area	Peri- meter	Ply	Bldr/ Deblk	Tape area	Tape prmtr
PART 26	48	4	192	104	8	1	0	0
PART 27	120	4	480	248	16	2	0	0
PART 28	48	4	192	104	16	2	0	0
PART 29	120	4	480	248	12	1	0	0
PART 30	48	4	192	248	12	1	0	0

APPENDIX B

ALUMINUM PARTS CONSTRUCTION

ALUMINUM PARTS CONSTRUCTION

The data for the aluminum parts were developed using the ICAM Manufacturing Cost/Design Guide. Each part is shown with the Cost Estimating Data (CED) charts or Designer Influenced Cost Elements (DICE) used in developing the part's cost. The entering arguments used for each part is also provided. The resulting numbers are standard hours or dollar costs for the 200th unit that must be adusted to the first unit cost which must be converted by an realization factor to the actual cost. The learning curve used to adjust all metal manufacturing processes is based on a 90 percent learning slope and is 2.25. Riveting is treated as a floor assembly process with a learning curve of 85 percent or correction factor of 3.48 (12:vol.1,pp.3-7,3-8). Once the number derived from the charts has been corrected to a unit one value, it must be multiplied by a 7.5 realization factor to obtain the number used in the thesis. The forging, casting, and extrusion processes have some elements which are expressed in dollars. To obtain hour values, the dollar values were divided by a wrap rate of 50 dollars an hour. The weight of the aluminum was determined by computing the volume of each part in cubic inches then multiplying that number by .1 pounds per cubic inch to obtain the pounds in the part. The material dollar cost was determined by mutiplying the part weight by the process

usage rate shown in Table 2. The nonrecurring tooling costs use a realization factor of 18.

When a part is used more than one time in the same assembly, it is preceded by the number of times it is used. If a part required more than one step to be fabricated, the main process is listed first with the other processes listed as steps 2 and on. DICE elements used in part construction are included as steps in developing the process. The number of rivets used in assembling a part was determined by summing the length of all of the ribs and spars in the part and dividing that value by .625. Stringers were not riveted except where they crossed a spar or a rib. It is assumed that they are either free standing or attached with a no cost adhesive. Dry riveting was used on every part but part 8 (the fuel cell), which use sealant on the rivet and the part being riveted (line 4). A ratio of 80 percent automatic riveting to 20 percent manual riveting was selected for all parts. A list of the CEDs and DICE elements that were used are provided below along with a brief desciption of the process.

ICAM MANUAL PROCESSES USED

CED	PAGE	ALUMINUM FABRICATION PROCESS
CED-A-1	4.1-44	angle, straight, brake form
CED-A-2	4.1-45	angle, curved, brake/roll
CED-A-3	4.1-46	angle, contoured, rubber press
CED-A-4	4.1-47	channel, straight , brake form
CED-A-5	4.1-48	channel, curved, brake/roll
CED-A-6	4.1-49	channel contoured, rubber press
CED-A-7	4.1-50	zee, straight, brake form
CED-A-8	4.1-51	zee, curved, brake/roll
CED-A-9	4.1-52	zee, contoured, rubber press
CED-A-10	4.1-53	lipped zee, straight, brake form
CED-A-11	4.1-54	lipped zee, curved, brake/roll
CED-A-12	4.1-55	lipped zee, contoured, brake/stretch
CED-A-16	4.1-59	lipped hat, straight, brake form
CED-A-17	4.1-60	lipped hat, curved, brake/roll
CED-A-18	4.1-61	lipped hat, contoured, brake/stretch
CED-A-19	4.1-62	flat sheet, routing only
CED-A-20	4.1-63	curved skin, farnham roll
CED-A-21	4.1-64	contoured skin, stretch form
CED-A-22	4.1-65	contoured fairing, drop hammer
CED-A-23	4.1-66	ribs & stamped shapes, rubber press
CED-A-24	4.1-67	beaded, corrogated panels, rubber press
DICE 1	4.1-91	summary of design influences
DICE 2	4.1-92	joggles (make end smaller for assembly)
DICE 3	4.1-93	flanged holes
DICE 6	4.1-96	solution heat treat
CED-MFA-1	4.2-24	installation cost for aluminum rivets
CED-MFA-3	4.2-26	nonrecurring tooling cost for riveting
CED-EXTN-6	4.4-34	extrusion tooling dies under 10"
CED-EXTN-8	4.4-36	extrusion lineal shapes
CED-EXTN-9	4.4-37	extrusion curved shapes
CED-EXTN-11	4.4-39	extrusion curved panels
DICE-EXTN-1	4.4-44	extusion joggle cost
DICE-EXTN-3	4.4-36	extrusion heat treatment
CED-C-1	4.5-43	sand casting base cost
CED-C-2	4.5-44	tool cost

LIST OF COMPLEX PARTS

PART 1: fuselage skin 96 X 36

Part	Process	Entering arguments
Skin	CED-EXTN-11	8 feet/slab is 96 X 36 X 2
2/spars	CED-A-11	8 feet/.1 thick T62 temper 394 sq in
4/ribs	CED-A-11	3 feet/.1 thick T62 temper 144 sq in
Rivets	CED-MFA-1	538 + 4 each intersection
step 2	CED-MFA-3	24 feet
Joggles	DICE-2	8

PART 2: fuselage skin 96 X 36

Skin	CED-A-20	24 sq ft/.14 thick, T3 temper
2/Spars	CED-A-11	8 feet/.1 thick T62 temper 384 sq in
4/Ribs	CED-A-11	3 feet/.1 thick T62 temper 144 sq in
8/Stringers	CED-A-7	8 feet/.1 thick T3 temper 192 sq in
Rivets	CED-MFA-1	538 + 4 each intersection/ 1.5 complexity factor used
step 2	CED-MFA-3	24 feet
Joggles	DICE-2	8

PART 3: tail opening cargo door 144 X 108 X 180 triangle

2/Skin	CED-A-20	27 sq ft/.2 thick, T3 temper
2/Border	CED-A-5	7.5 feet/.063 thick T3 temper
2/Border	CED-A-5	12 feet/.063 thick T3 temper
Border	CED-A-5	9 feet/.063 thick T3 temper
Rib	CED-A-5	9 feet/.063 thick T3 temper
Rib	CED-A-5	6 feet/.063 thick T3 temper
Rib	CED-A-5	3 feet/.063 thick T3 temper
15/Stringers	CED-A-7	11'4" down to 4'2" with one every 8 inches/.063 thick T3 temper
Rivets	CED-MFA-1	1268 + 4 each intersection 1.5 complexity factor used
step 2	CED-MFA-3	extrapolated, 800 used

All borders and ribs are 4 in tall, stringers are 2 in tall

PART 4: low speed leading edge 120 X 60 area

Skin	CED-A-20	50 sq ft/.1 thick T3 temper
13/ribs	CED-A-23	1.5 sq ft/.063 thick
Rivets	CED-MFA-1	1248
step 2	CED-MFA-3	20 sq ft (10 long, 2 high)

PART 5: rudder overall dimensions 40 X 18

2/Skins	CED-A-19	3.75 sq ft/.1 thick T3 temper
Spar	CED-EXTN-6	2.2 in/ divide by $50
step 2	CED-EXTN-8	3.33 ft/.3 thick
step 3	DICE-EXTN-3	3.33 ft, I shape 2 X 2
5/Ribs	CED-C-1	30 cu in box volume/.1 thick divide by $50, mil A-21180
step 2	CED-C-2	30 cu in box volume/.1 thick divide by $50, ribs are triangles with 1 in wide border. ave ht = 15, base = 2
Rivets	CED-MFA-1	356
step 2	CED-MFA-3	10 feet

PART 6: Aileron 36 X 24

2/Skins	CED-A-19	6 sq ft/.14 thick T3 temper
Spar/rib assy	CED-C-1	1728 box volume/divide by $50 .1 thick, mil A-21180
step 2	CED-C-2	1728 box volume/.1 thick divide by $50 overall part is C shaped 2 in. thick with spar I 2 X 2 in shape and ribs are triangles with 1 in wide border and 2 in base
Honeycomb	FACET	see composite part 6
Assembly	FACET	see composite part 6

PART 7: Wingbox 120 X 36 X 12

2/Skins	CED-A-19	30 sq ft/.25 thick, T3 temper
2/Spars	CED-A-19	10 sq ft/.14 thick, T3 temper
step 2	CED-A-1	10 ft/.14 thick T62 temper 4 angles per plate for I beam angles .063 thick 480 sq in
4/Ribs	CED-A-19	3 sq ft/.14 thick T3 temper
step 2	CED-A-1	2 angles per plate for C rib angles .063 thick 144 sq in
10/stringer	CED-A-7	10 ft/.063 thick, 360 sq in
Rivets	CED-MFA-1	1996
step 2	CED-MFA-3	24 feet
Joggles	DICE-2	60
Holes	DICE-3	30

PART 8: fuel cell 120 X 36 X 12

2/Skins	CED-A-19	30 sq ft/.25 thick, T3 temper
2/Spars	CED-A-19	10 sq ft/.14 thick, T3 temper
step 2	CED-A-1	10 ft/.14 thick T62 temper 4 angles per plate for I beam angles .063 thick 480 sq in
4/Ribs	CED-A-19	3 sq ft/.14 thick T3 temper
step 2	CED-A-1	2 angles per plate for C rib angles .063 thick 144 sq in
10/stringer	CED-A-7	10 ft/.063 thick, 360 sq in
Rivets	CED-MFA-1	1996/ use line 4
step 2	CED-MFA-3	24 feet
Joggles	DICE-2	60
Holes	DICE-3	30

PART 9: aileron, low speed 36 X 24

Skin	CED-A-19	6 sq ft/.056 thick T3
Spar	CED-A-4	3.5 ft/.2 thick T62 160 sq in
5/ribs	CED-A-23	2 ft/.063 thick T3, 62 sq in
Rivets	CED-MFA-1	442
step 2	CED-MFA-3	10 ft.

PART 10: fuselage skin 60 X 24

Skin	CED-A-20	10 sq ft/.2 thick
2/Spars	CED-A-11	5 ft/.063 thick 360 sq in
4/Ribs	CED-A-11	2 ft/.063 thick 88 sq in
Rivets	CED-MFA-1	346
step 2	CED-MFA-3	10 ft
Joggle	DICE-2	8

LIST OF SIMPLE PARTS

PART 11: panel 48 X 36

Part	Process	Entering arguments
Skin	CED-A-21	12 sq ft/.063 thick
Support	CED-A-22	12 sq ft/.063 thick
cutouts	DICE-1	19 ft of perimeter
rivets	CED-MFA-1	190 (panel, reduced number)
step 2	CED-MFA-3	12 ft

PART 12: spar 48 X 6 X 6

Webbing	CED-A-19	1 sq ft/.1 thick
4/Angles	CED-A-1	4 ft/.063 thick 4 in. wide
Rivets	CED-MFA-1	148
step 2	CED-MFA-3	9 ft

All parts T3 temper

PART 13: curved rib 48 X 4

Rib	CED-A-5	4 ft/.063 thick 4 in. wide T3 temper

PART 14: straight rib 48 X 4

Rib	CED-A-4	4 ft/.063 thick 4 in. wide T3 temper

PART 15: panel 36 X 24

Skin	CED-A-20	6 sq ft/.063 thick T81 temper
Corrogation	CED-A-24	6 sq ft/.063 thick T81 temper
Rivets	CED-MFA-1	192 rivets
step 2	CED-MFA-3	10 ft.

PART 16: panel 36 X 24

Skin	CED-A-20	6 sq ft/.14 thick T3 temper

PART 17: panel 36 X 24

2/Skins	CED-A-22	6 sq ft/.14 thick
Honeycomb	FACET	see composite part 17
Assembly	FACET	see composite part 17

PART 18: fairing 24 X 12

Fairing	CED-A-22	2 sq ft/.1 thick

PART 19: fairing 120 X 36

Half fairing	CED-A-22	15 sq ft/.2 thick
Half fairing	CED-A-22	15 sq ft/.2 thick

Count tooling costs for both halves since their shapes are different.

PART 20: curved skin 60 X 24

Skin	CED-A-21	10 sq ft/.14 thick

PART 21: spar 120 X 12 X 6

Webbing	CED-A-19	10 sq ft/.1 thick
4/Angles	CED-A-1	10 ft/.063 thick 4 in. wide
Rivets	CED-MFA-1	384
step 2	CED-MFA-3	22 ft

All parts T3 temper

PART 22: curved hat shaped stringer 120 X 4

Stringer	CED-A-17	10 ft/.063 thick T62 temper

PART 23: curved hat shaped stringer 48 X 4

Stringer	CED-A-17	4 ft/.063 thick T62 temper

PART 24: straight hat shaped stringer 120 X 4

Stringer	CED-A-16	10 ft/.063 thick T3 temper

PART 25: straight hat shaped stringer 48 X 4

Stringer	CED-A-16	4 ft/.063 thick T3 temper

PART 26: straight rib 48 X 4

Rib	CED-A-4	4 ft/.056 thick T3 temper

PART 27: straight "L" shaped stiffener 120 X 4

Stiffener CED-A-1 10 ft/.063 thick T62 temper

PART 28: straight "L" shaped stiffener 48 X 4

Stiffener CED-A-1 4 ft/.063 thick T62 temper

PART 29: curved "L" shaped stiffener 120 X 4

Stiffener CED-A-2 10 ft/.063 thick T3 temper

PART 30: curved "L" shaped stiffener 48 X 4

stiffener CED-A-2 4 ft/.063 thick T3 temper

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